Probing Radiative Neutrino Mass Generation through Monotop Production

Alejandro de la Puente

TRIUMF, Theory Group

Fermilab

Theory Seminar

May 8, 2014

Based on arXiv:1307.2606 and arXiv:1404.1415 in collaboration with John Ng.

Outline

- Motivation
- Model
    - Dark Matter
    - Neutrinos masses
- Constraints
- Monotop Probe
- Summary

Motivation

- **Two important questions in the field of High Energy physics:**
- **Neutrino mass generation.**

- **Nature of Dark Matter.**

- **Cosmological results based on Planck's measurements of the CMB:**
- $\Omega_c h^2 = 0.1199 \pm 0.0027$

- $N_{eff} = 3.30 \pm 0.27$ **Planck Collaboration arXiv:1303.5076**

- **Neutrinos have played an important role in testing:**
    - Standard Model.
    - Structure of the nucleon.
    - Dynamics of core collapse supernovae, etc.

- **Neutrino masses still intrigue us...**
    - Sensitive to large new physics scales or scales as low as a TeV.
    - Two mixing angles are large.
    - CP violation.
    - Dirac or Majorana?
    - Absolute mass scale and mass ordering.

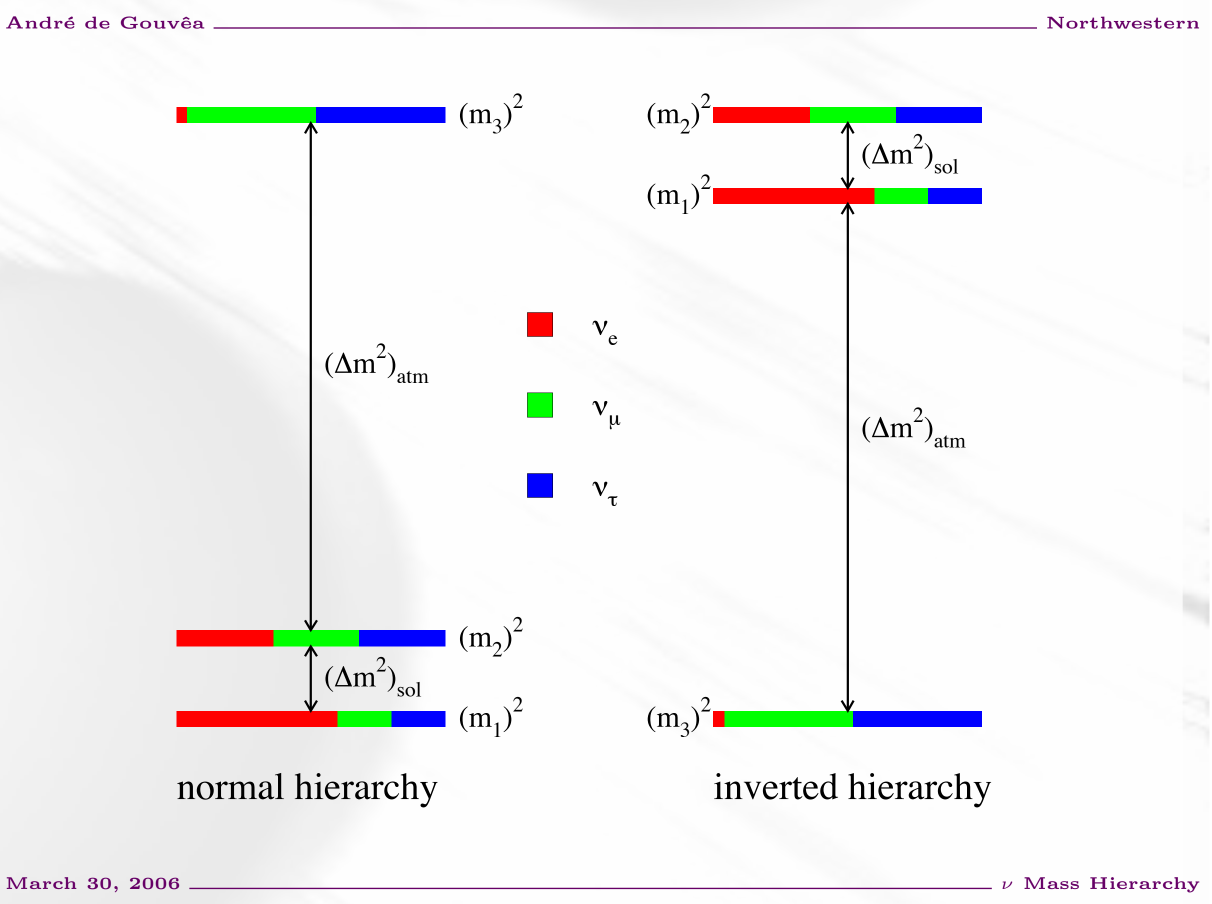
Status: Oscillations sensitive to neutrino masses.

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}s_{13}s_{23}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}s_{13}s_{23}\,e^{i\delta} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}s_{13}c_{23}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}s_{13}c_{23}\,e^{i\delta} & c_{13}\,c_{23} \end{pmatrix}$$

$$\begin{aligned}
\Delta m^2_{21} &= (7.50 \pm 0.185) \times 10^{-5}\,\mathrm{eV}^2 \\
\sin^2\theta_{12} &= 0.30 \pm 0.013 \\
\Delta m^2_{31} &= (+2.47 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2 \;\; \text{(normal ordering)} \\
\Delta m^2_{32} &= (-2.43 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2 \;\; \text{(inverted ordering)} \\
\sin^2\theta_{13} &= 0.023 \pm 0.0023 \\
\sin^2\theta_{23} &= \begin{cases} 0.41 \pm 0.037 & (1^{\text{st}} \text{ octant}) \\ 0.59 \pm 0.022 & (2^{\text{nd}} \text{ octant}) \end{cases}
\end{aligned}$$

arXiv:1209.3023

- **See "Neutrino Oscillations: Present and Future" by Chang Kee Jung, Plenary session at PHENO 2014.**
- **ν_e - appearance to probe CPV phase.**



A. de Gouvea 2006

- **Introduce a model of physics beyond the Standard Model which can naturally generate small neutrino masses while providing a viable candidate for the dark matter present in our universe.**

- **Neutrinos in the Standard Model:**
  - **Active neutrinos:**
    - **SU(2) doublet with a charged lepton.**
    - **Three flavours:** ν_e, ν_μ, ν_τ
  - **Sterile neutrinos:**
    - **SU(2) singlet:** ν_R
    - **Allowed interactions are through Higgs, mixing, or BSM interactions.**

- **Dirac masses:**
  - **Can be generated by *vev* of Higgs doublet.**

$$\mathcal{L} \supset \bar{L}_\alpha Y_{i,\alpha} \nu_{R,i} H$$

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$$\mathcal{L} \supset \bar{L}_\alpha Y_{i,\alpha} \nu_{R,i} H$$

$$\Rightarrow \quad m_D = y_d \langle H \rangle$$

$$y_D \sim 10^{-12}$$
$$m_D \sim 0.1 \text{ eV}$$

- **Dirac masses:**
  - **Can be generated by *vev* of Higgs doublet.**

$$\mathcal{L} \supset \bar{L}_\alpha Y_{i,\alpha} \nu_{R,i} H$$

- **Majorana masses:**
  - **For active neutrinos, can generate them through a Higgs triplet.**

Seesaw Mechanism (Type I):

Yanagida.
M. Gell-Mann, P. Ramond, R. Slansky.
R.N. Mohapatra, G. Senjanovic

$$\mathcal{L} \supset \frac{1}{2}\bar{\nu}^c_{R,i} \left(M_R\right)_{i,j} \nu_{R,j} + \bar{L}_\alpha \left(Y_D\right)_{i,\alpha} \nu_{R,i} H$$

$\Rightarrow$ $m_\nu = -m_D M_R^{-1} m_D^T$ $\Rightarrow$ $M_R \sim 10^{15}$ with $m_D \sim \langle H \rangle$

- **Need to test the Higgs vertex:**
  - **Formidable task since we don't know the nature of m_ν.**
  - **Assumptions can be made, i.e. $m_D \to m_{q_u}$ such as in SO(10) models.**

Other mechanisms:

- **Type II seesaw:** Adds an $SU(2)_W$ Higgs triplet which couples to the SM lepton doublet generating a Majorana mass term for left-handed neutrinos.

- **Type III seesaw:** Adds an $SU(2)_W$ fermion triplet which couples to the SM lepton doublet generating a Dirac mass for left-handed neutrinos.

- Radiative seesaw models.

- Supersymmetric extensions, etc.

Model

- Use the top quark as a dark portal and for neutrino mass generation:

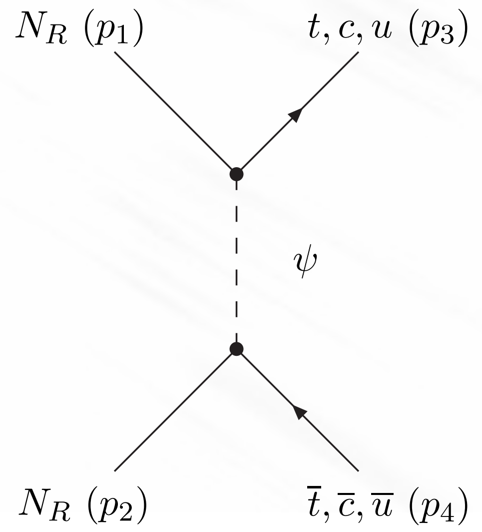
Dark Matter:

- **Extension of the Standard Model:**
  - **Z_2 yields a viable dark matter candidate.** $M_{N_R} < m_\psi$

$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_\psi^{u_i} \bar{u}_i P_L N^c \psi + \text{ h.c.}$$

$$N : (\mathbf{1}, \mathbf{1}, \mathbf{0})$$

$$\psi : (\mathbf{3}, \mathbf{1}, \mathbf{2/3})$$



Y. Bai and J. Berger
S. Chang, R. Edezhath, J. Hutchinson, and M. Luty
H. An, L. -T. Wang and H. Zhang
A. DiFranzo, K. I. Nagao, A. Rajaraman, and T. M. P. Tait
M. Garny, A. Ibarra, S. Rydbeck, and S. Vogl

- **See "Dark Matter at Colliders" by Lian-Tao Wang, Invited Review at PHENO 2014.**

Dark Matter:

• We use a low velocity expansion of the annihilation cross section.

• Annihilation only into lights quarks is p-wave suppressed.

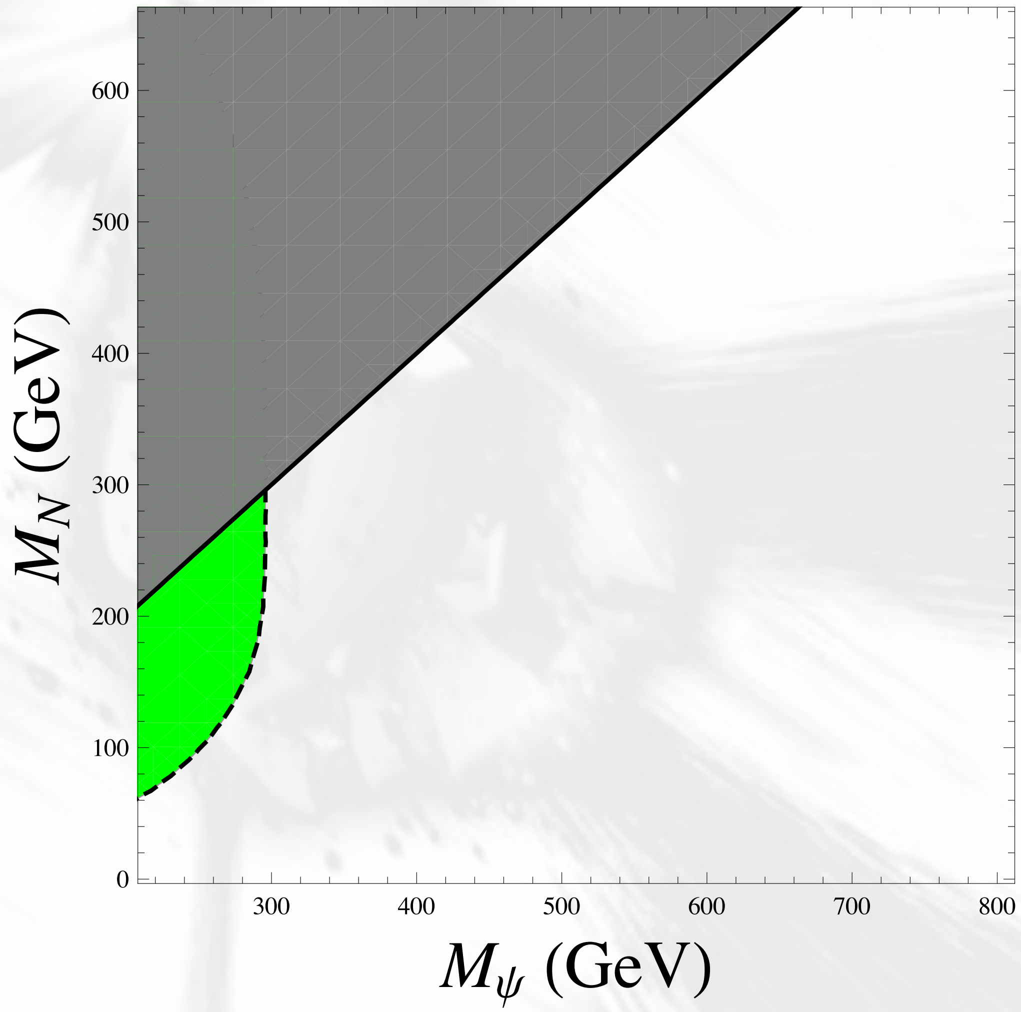
$$\langle \sigma_{N_R N_R} v \rangle \approx v_{rel}^2 \left[(y_\psi^u)^4 + (y_\psi^c)^4 \right] \frac{m_{N_R}^2 (m_{N_R}^4 + m_\psi^4)}{16\pi (m_{N_R}^2 + m_\psi^2)^4}$$

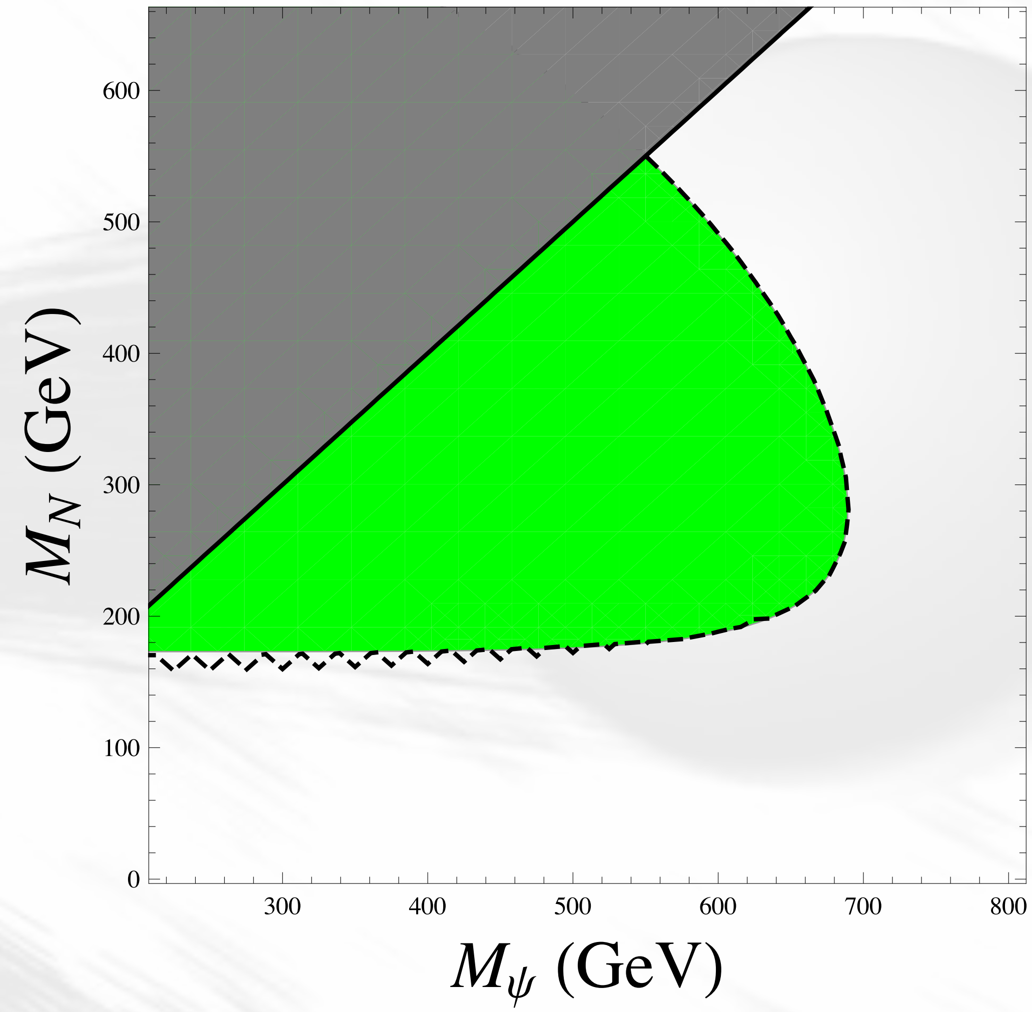
Dark Matter:

- We use a low velocity expansion of the annihilation cross section.

- Non-zero coupling to the top-quark leads to an s-wave contribution.

$$\langle \sigma_{N_R N_R} v \rangle \approx \frac{3 m_t^2 (y_\psi^t)^2}{128 \pi M_{N_R}^4} \left(\frac{4 (y_\psi^t)^2 M_{N_R}^3 \sqrt{(M_{N_R} - m_t)(M_{N_R} + m_t)}}{(M_{N_R}^2 - m_t^2 + m_\psi^2)^2} - \frac{[(y_\psi^u)^2 + (y_\psi^c)^2](4 M_{N_R}^2 - m_t^2)^2}{2(2M_{N_R}^2 - m_t^2 + 2 m_\psi^2)^2} \right)$$





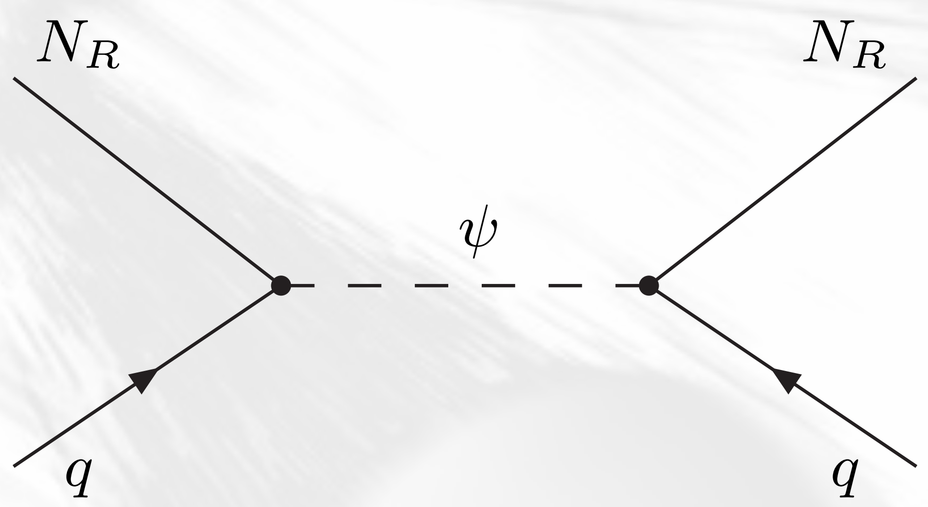
c-quark **t-quark**

- **Co-annihilation effects can be safely neglected:**

$$N_R \psi^\dagger \to u/c/t\ g,\ \psi\psi^\dagger$$

Direct Detection:

- **Majorana fermion with chiral symmetric interactions:**
- **Scattering is dominated by spin dependent interactions.**



$$\mathcal{M} = \frac{(y^u_\psi)^2}{4(m_\psi^2 - M_{N_R}^2)} \bar{N}_R \gamma^\mu \gamma^5 N_R \left\langle \bar{u} \gamma_\mu \gamma^5 u \right\rangle$$

Direct Detection:

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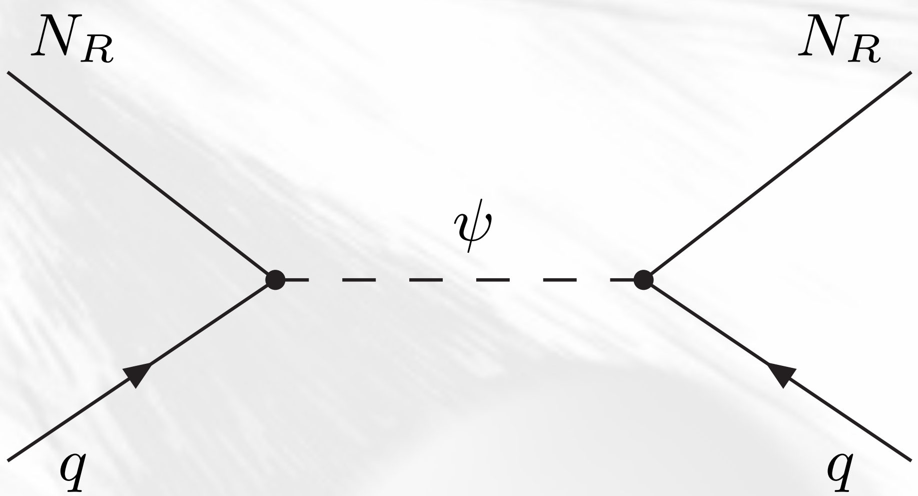
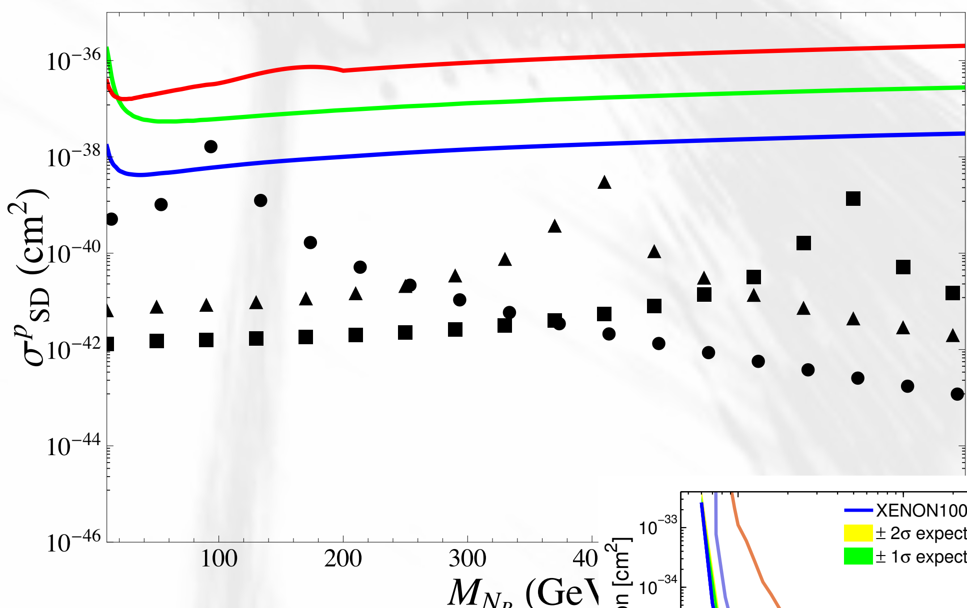


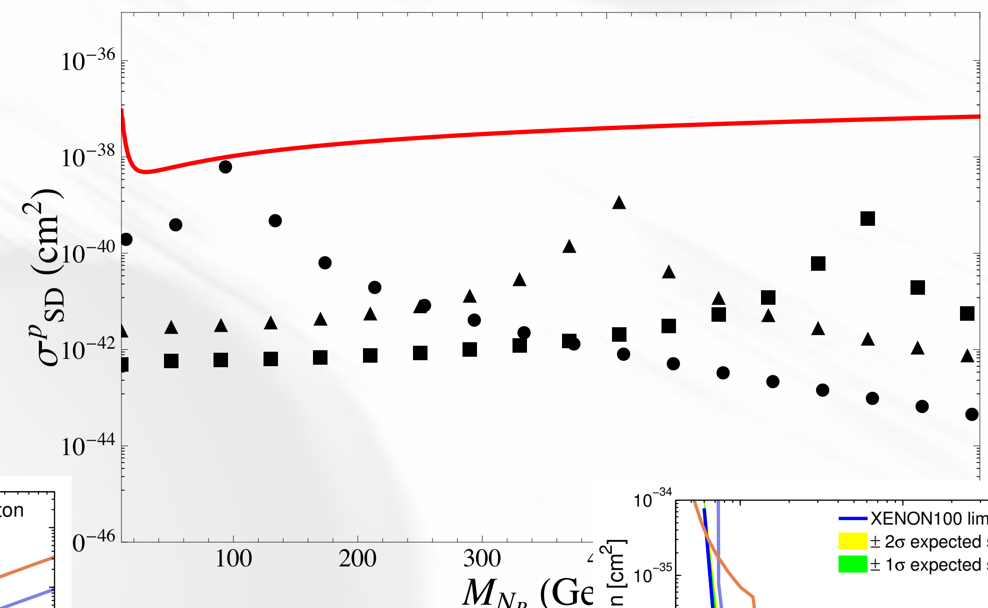
- Dimension-7 operators are loop induced and lead to spin independent interactions: $\mathcal{O}_2 = \frac{\alpha_S}{4\pi} G^{a\mu\nu} G^a_{\mu\nu} N_R^2$, $\mathcal{O}_3 = m_q \bar{q} q N_R^2$

Dark matter - nucleon scattering: $y_\psi^u = 0.5$

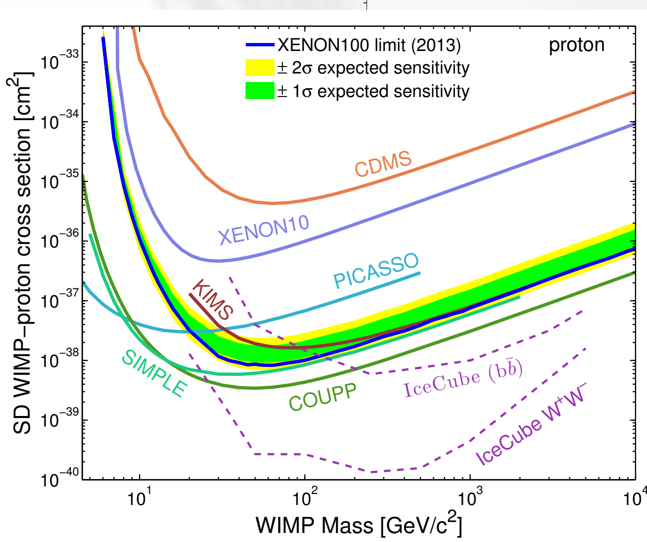
protons

neutrons



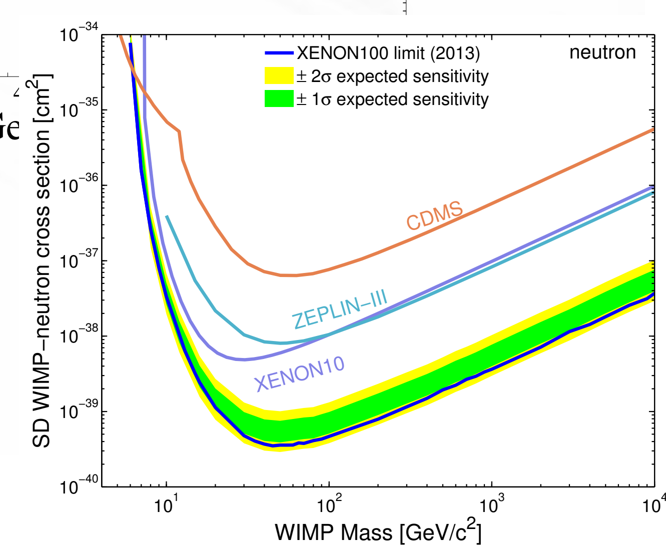


- COUPP arXiv:1008.3518
- PICASSO arXiv:1106.3014
- SIMPLE arXiv:1106.3014



- XENON10 arXiv:0805.2939

arXiv:1301.6620



Neutrino mass generation:

- Conserved Z_2 prevents Dirac neutrino mass terms for the active neutrinos.
    - Incorporate two coloured electroweak-triplet scalars.

$$\chi = \begin{pmatrix} \chi_2/\sqrt{2} & \chi_1 \\ \chi_3 & -\chi_2/\sqrt{2} \end{pmatrix} : (\mathbf{3}, \mathbf{3}, -\mathbf{1}/\mathbf{3})$$

$$\omega = \begin{pmatrix} \omega_2/\sqrt{2} & \omega_1 \\ \omega_3 & -\omega_2/\sqrt{2} \end{pmatrix} : (\mathbf{3}, \mathbf{3}, \mathbf{2}/\mathbf{3})$$

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$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_\psi^{u_i} \bar{u}_i P_L N^c \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_\ell \left[\bar{t} P_R \left(\chi_1 \nu_\ell^c + \chi_2 \ell^c \right) + \bar{b} P_R \left(\chi_3 \ell^c - \chi_2 \nu_\ell^c \right) \right] \right\} + \frac{1}{2} M_{N_R} \bar{N}^c N + \text{ h.c.}$$

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$$\begin{aligned} V(H,\psi,\chi,\omega) &= -\mu^2 H^\dagger H + \frac{\lambda}{4!}(H^\dagger H)^2 + m_\chi^2 Tr\left(\chi^\dagger \chi\right) + m_\omega^2 Tr\left(\omega^\dagger \omega\right) + m_\psi^2 \psi^\dagger \psi + \lambda_\chi \left(Tr \chi^\dagger \chi\right)^2 \\ &+ \lambda_\omega (Tr \omega^\dagger \omega)^2 + \lambda_\psi \left(\psi^\dagger \psi\right)^2 + \kappa_1 H^\dagger H \left(Tr \chi^\dagger \chi\right) + \kappa_2 H^\dagger \chi^\dagger \chi H \\ &+ \kappa_3 H^\dagger H \psi^\dagger \psi + \kappa_4 H^\dagger H Tr \omega^\dagger \omega + \kappa_5 H^\dagger \omega^\dagger \omega H + \rho_1 \left(Tr \chi^\dagger \chi\right) \psi^\dagger \psi \\ &+ \rho_2 \left(Tr \omega^\dagger \omega\right) \psi^\dagger \psi + \rho_3 Tr\left(\omega^\dagger \psi \omega^\dagger \psi\right) + \alpha Tr H^T \sigma_2 \chi \omega^\dagger H + \tilde{V}(\chi,\omega) + \text{h.c} \end{aligned}$$

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Leads to $\chi - \omega$ mixing.

$$\theta_{\chi-\omega} \propto \alpha v^2/\bar{M}^2$$

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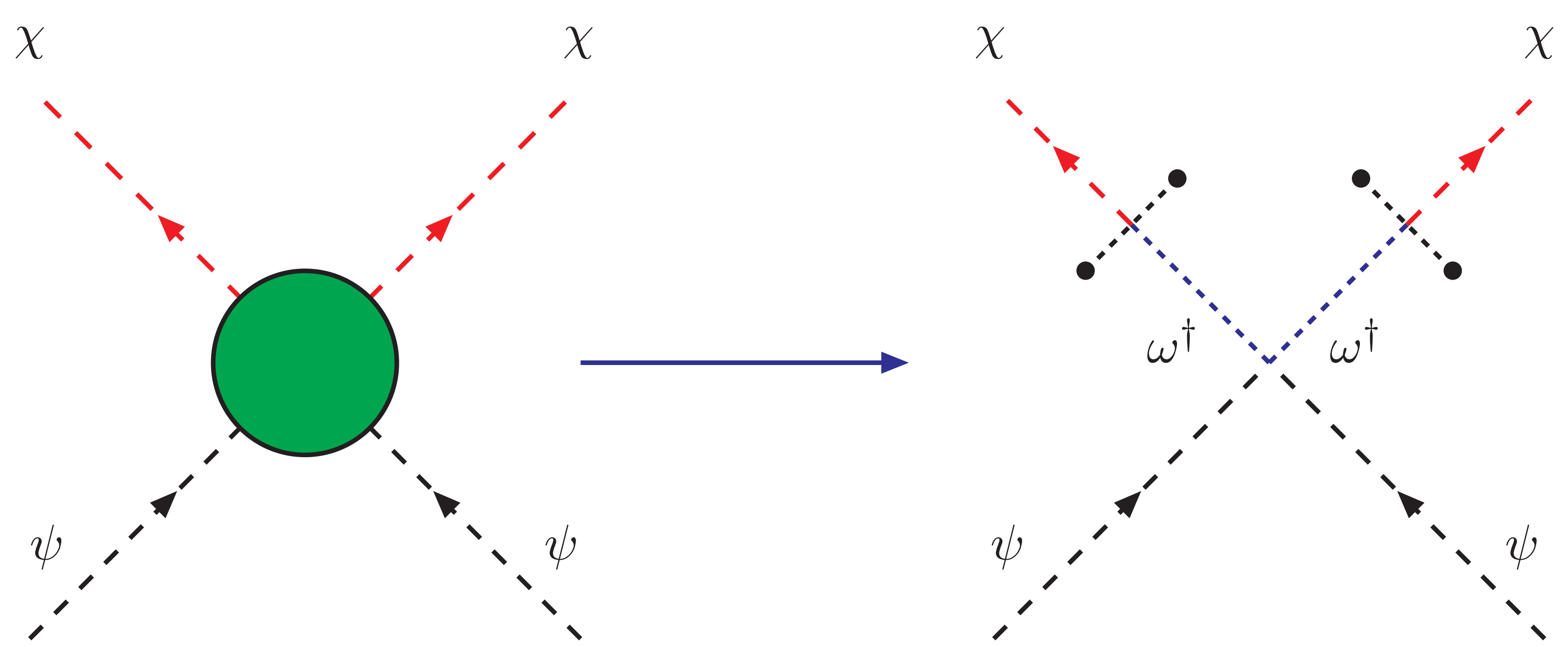

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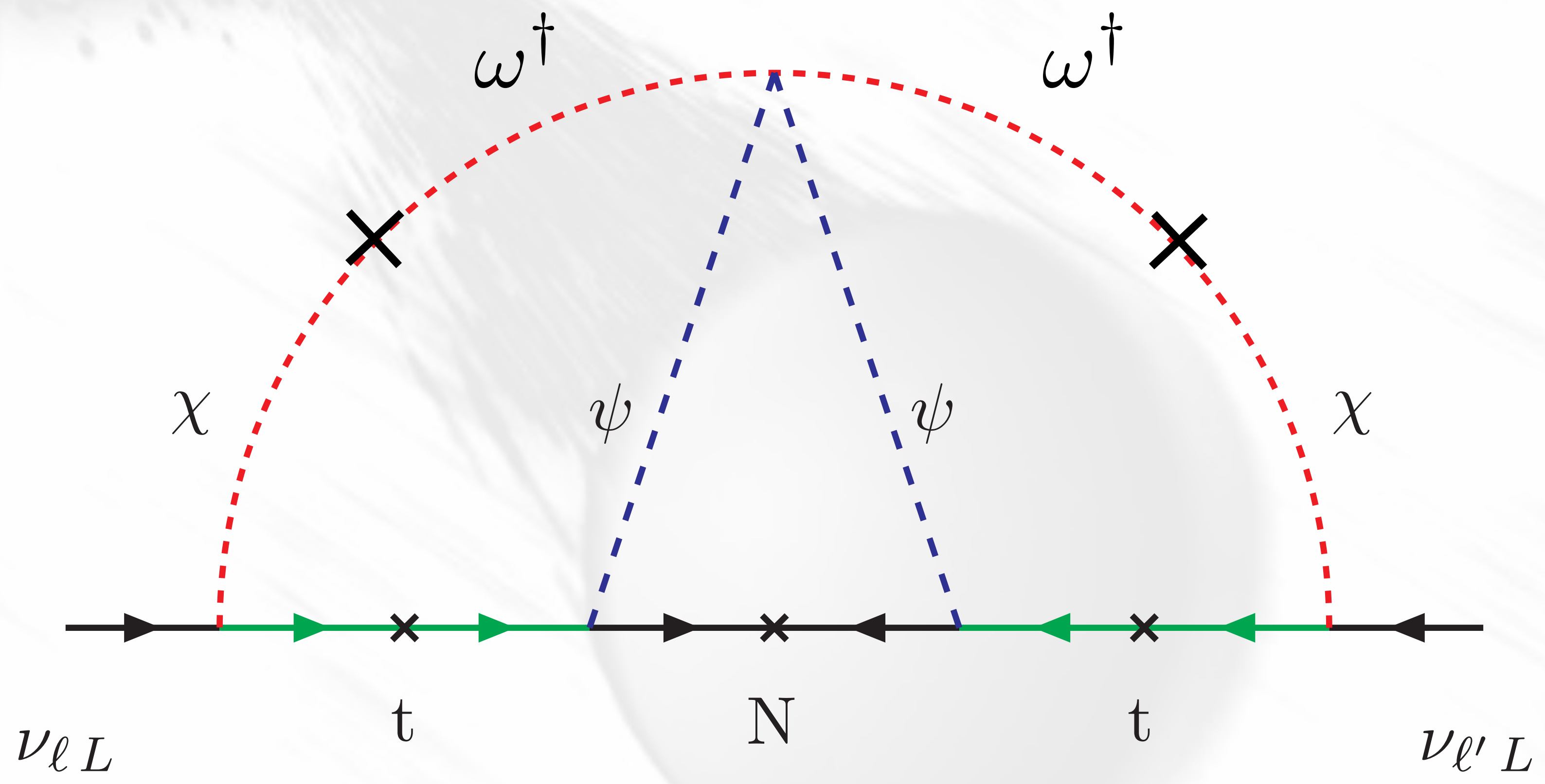

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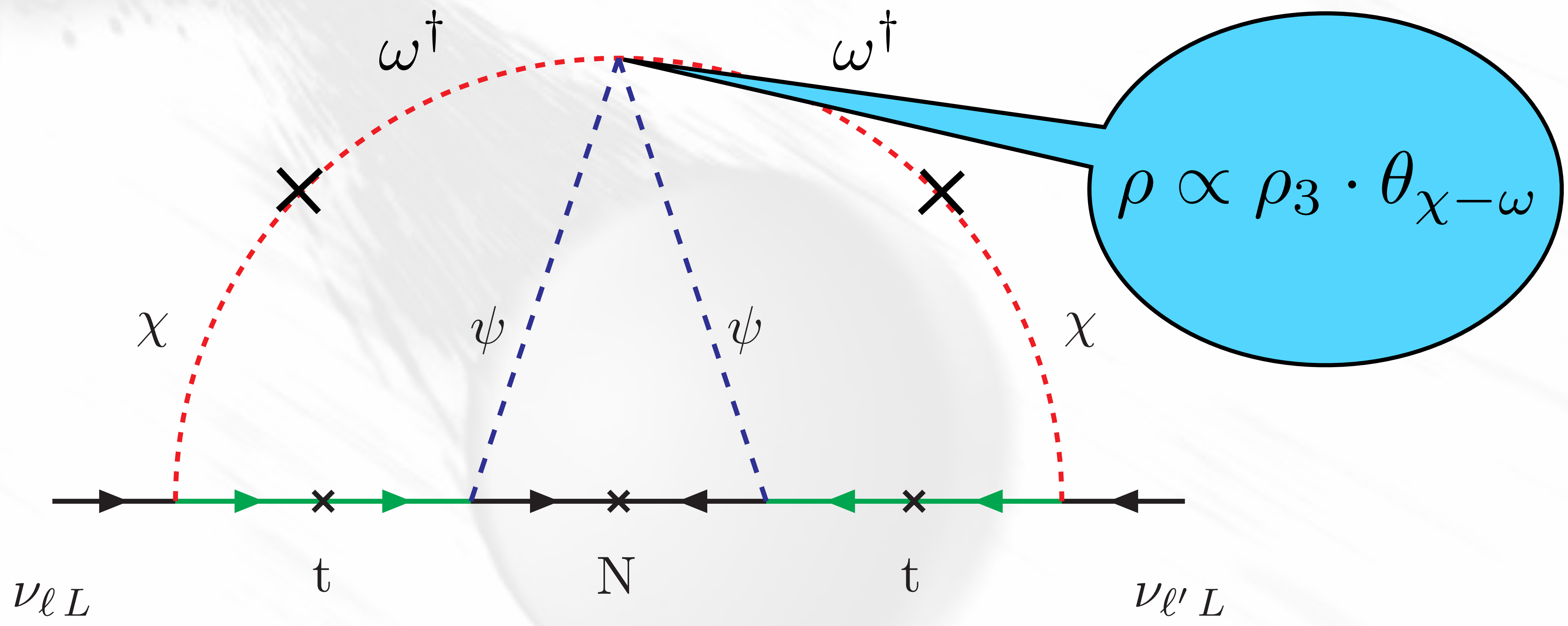
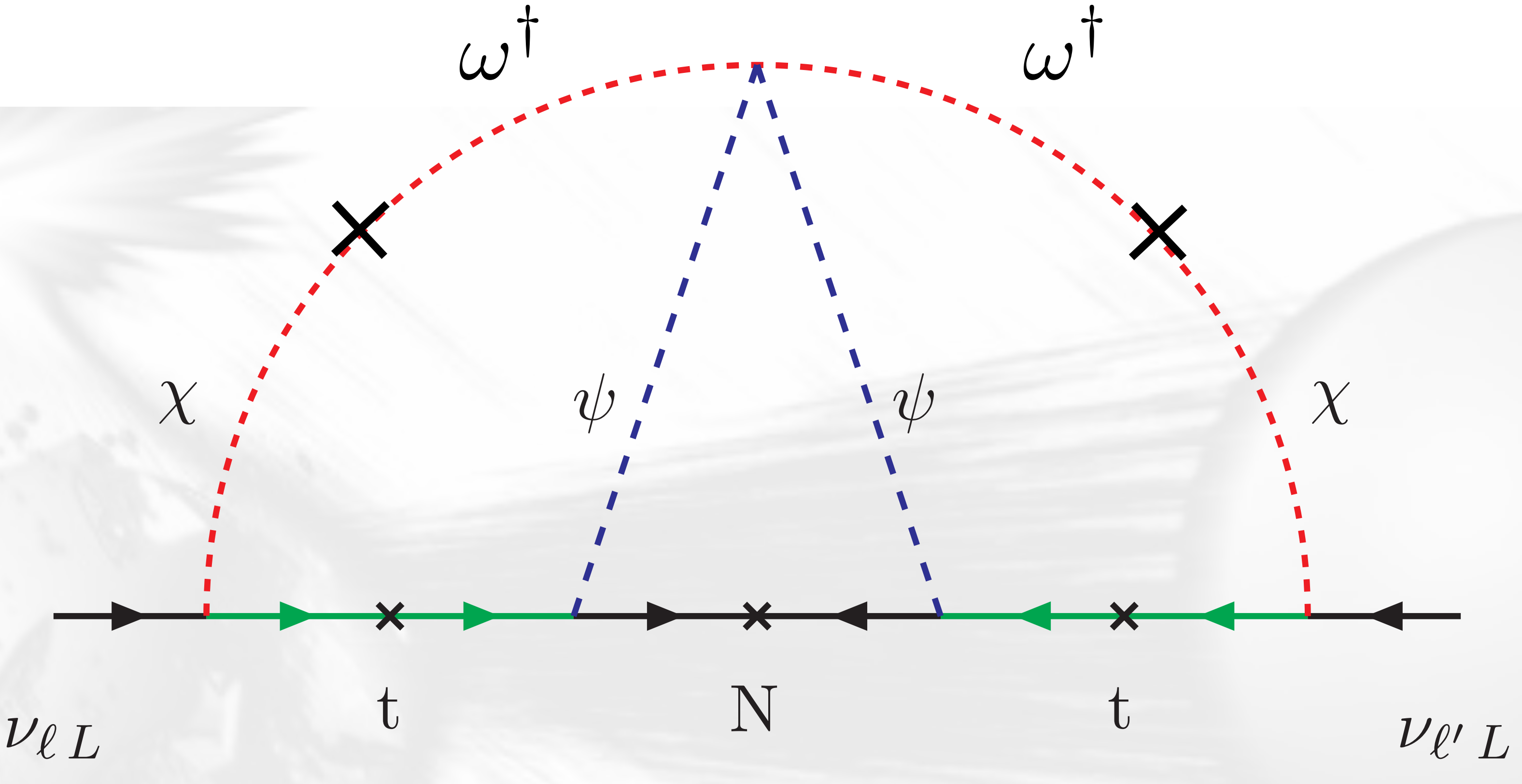


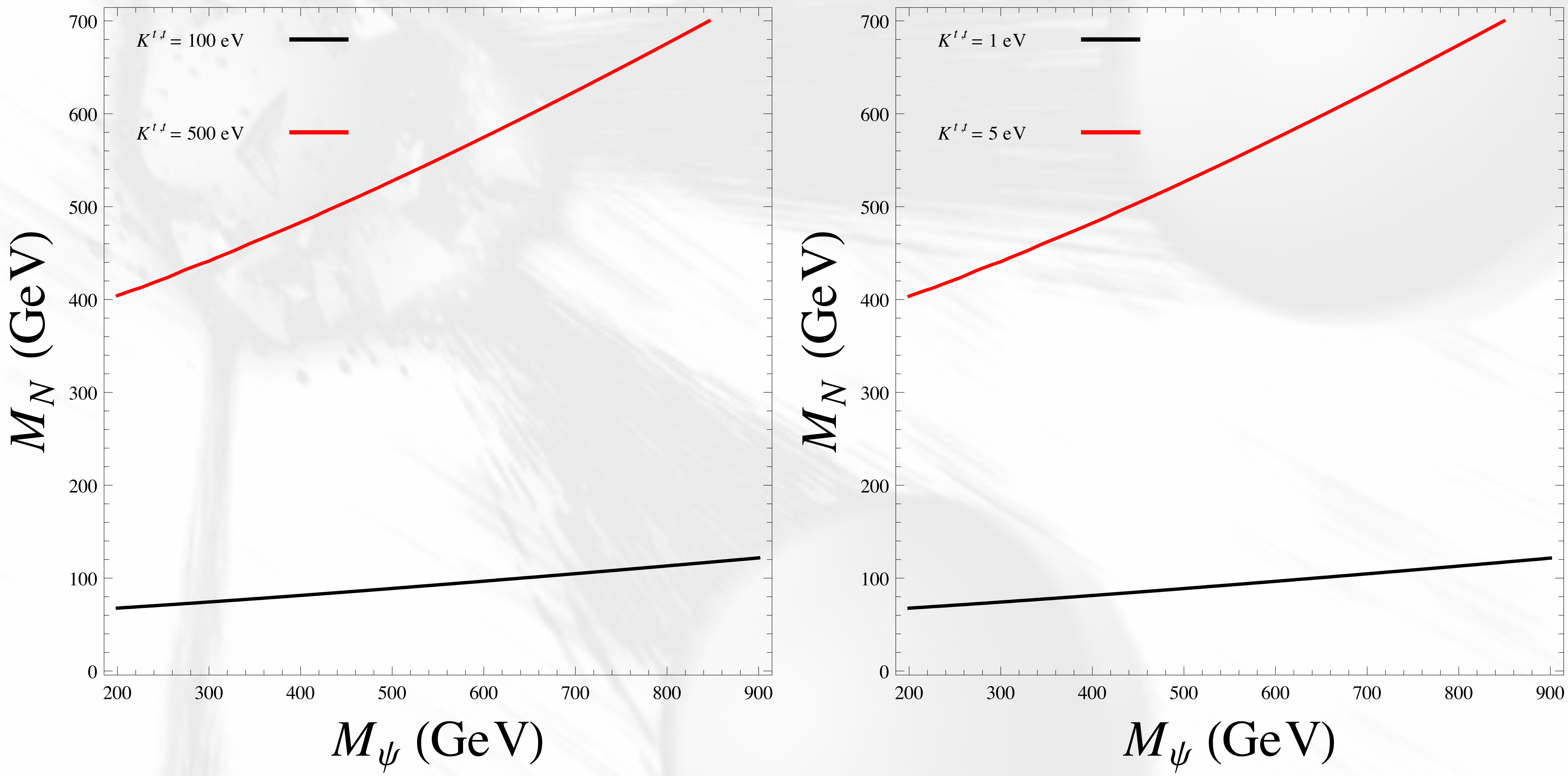


$$(M_\nu)_{\ell\ell'} = \sum_{i,j} K^{ij} \lambda^i_\ell \lambda^j_{\ell'}$$

$$K^{ij} \quad = \quad \frac{y^i_\psi y^j_\psi \rho}{(16\pi^2)^3} \frac{m_i m_j \, M_{N_R}}{(m^2_\chi - m^2_i)(m^2_\chi - m^2_j)} I(m^2_\chi, m^2_\psi, m^2_i, m^2_j),$$

$$\Rightarrow \quad (M^\nu)_{ll'} = \sum_{i,j} K^{i,j} \lambda^i_l \lambda^j_{l'}$$

$$\rho = 0.1,\ m_\chi = 1\ \text{TeV}$$



$y_\psi^t \approx 1$ $\qquad$ $y_\psi^t \approx 0$

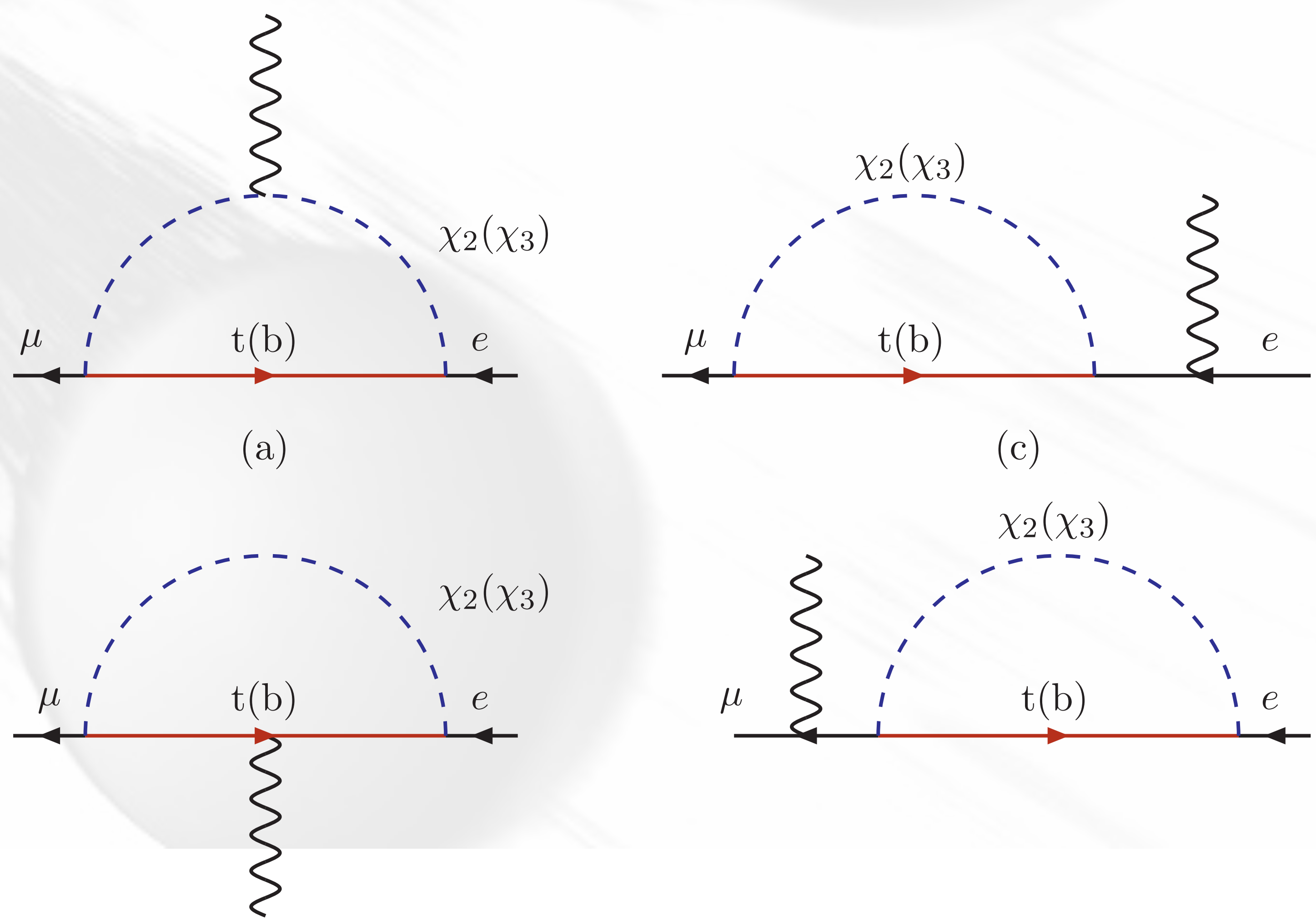
Constraints

- **Rare muon and b decays:** **Sensitive to coloured electroweak-triplets.**

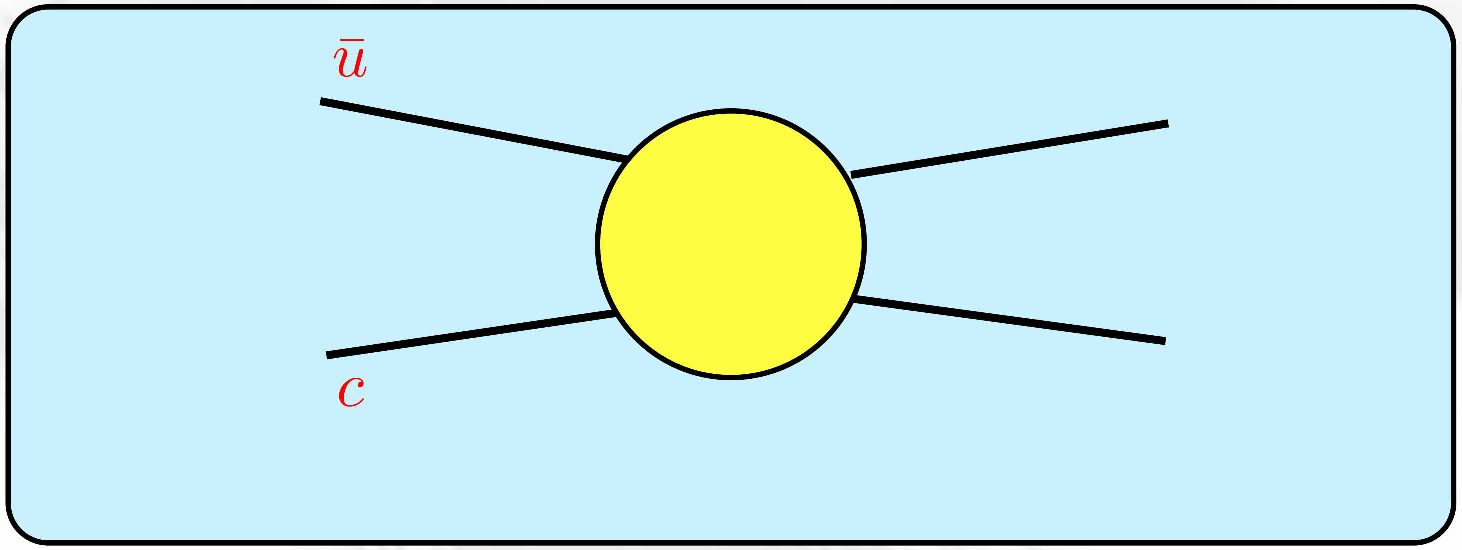
$$\mathcal{L}_{BSM} = \sum_{i=u,c,t} y_{\psi}^{u_i} \bar{u}_i P_L N^c \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_\ell \left[\bar{t} P_R \left(\chi_1 \nu_\ell^c + \chi_2 \ell^c \right) + \bar{b} P_R \left(\chi_3 \ell^c - \chi_2 \nu_\ell^c \right) \right] \right\} + \text{ h.c.}$$

$$\begin{aligned} Br\left(\mu \to e\gamma\right) &= 7.2 \times 10^{-6} \left(\frac{m_{e\mu}}{K^{t,t}}\right) \\ m_{e\mu} &= 1.5 - 8.8 \text{ meV} \end{aligned}$$

arXiv:1107.5547
arXiv:1302.0653



- **D meson oscillations:**



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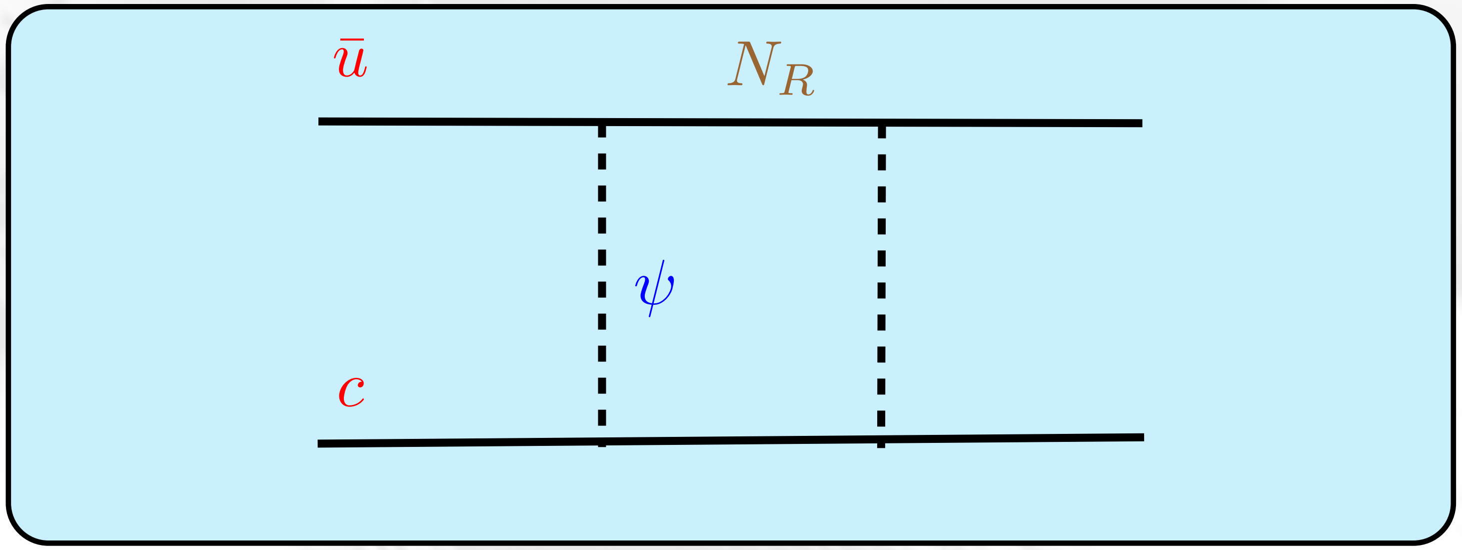
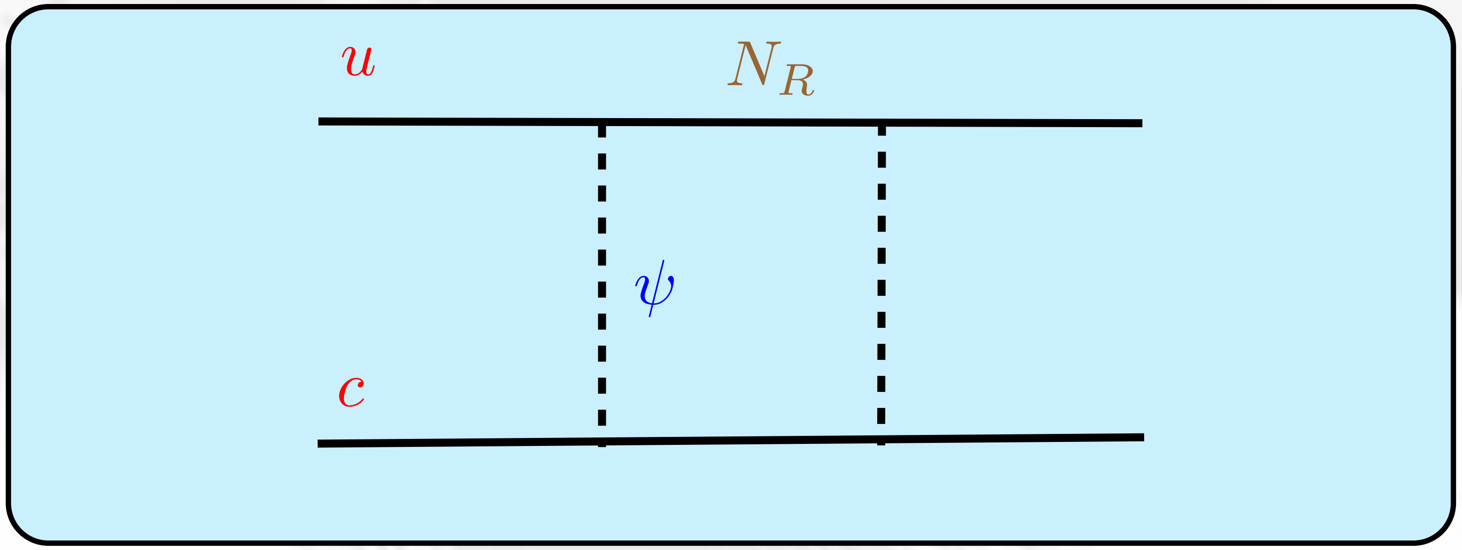


$$Q_6 = \left(\bar{u}_R \gamma_\mu c_R\right)\left(\bar{u}_R \gamma^\mu c_R\right)$$

$$\Delta M_D = \frac{\left(y_\psi^u y_\psi^c\right)^2 f_D M_D}{64\pi^2 m_\psi} \frac{2}{3} B_D \beta(m_c, m_{m_\psi}) |L(\eta)|$$

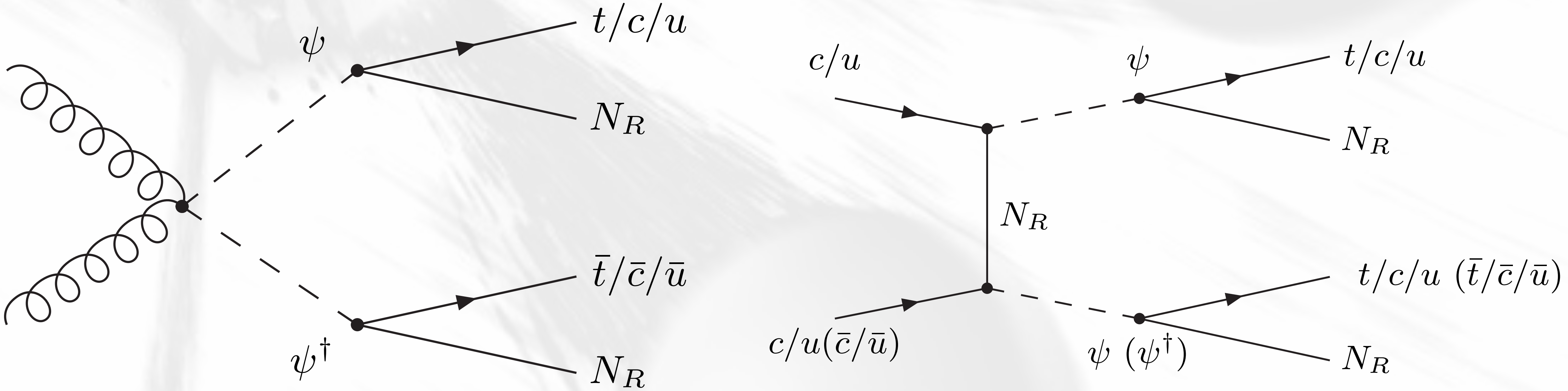
• D meson oscillations:



$$Q_6 = (\bar{u}_R \gamma_\mu c_R)\,(\bar{u}_R \gamma^\mu c_R)$$

- $x_D = \dfrac{\Delta M_D}{\Gamma_D} = 0.43^{+0.15}_{-0.16}\,\%$. arXiv:1207.1158

- **<u>Collider constraints:</u> SUSY searches (stop pair production), monojet+MET and jets+MET**



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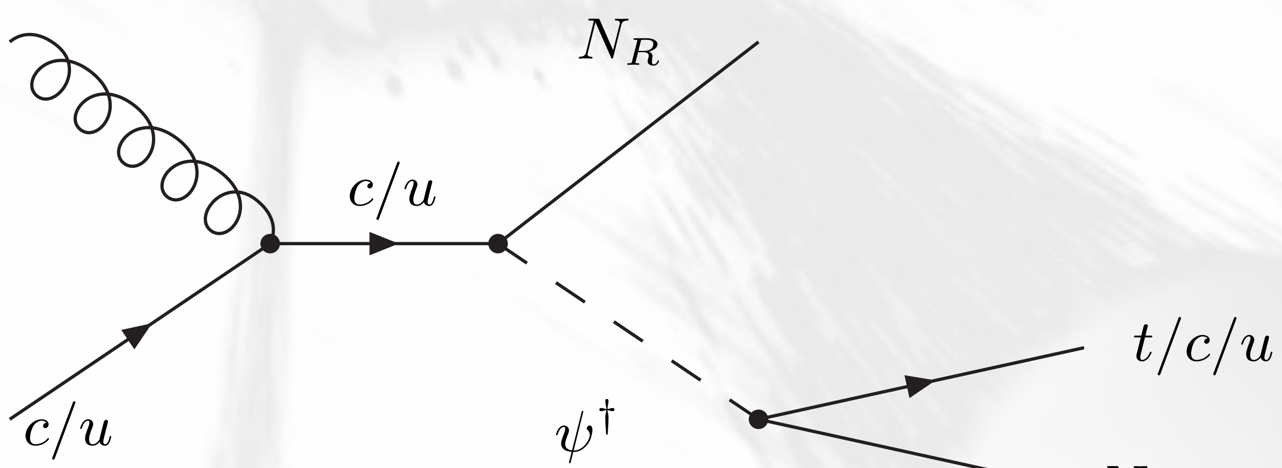

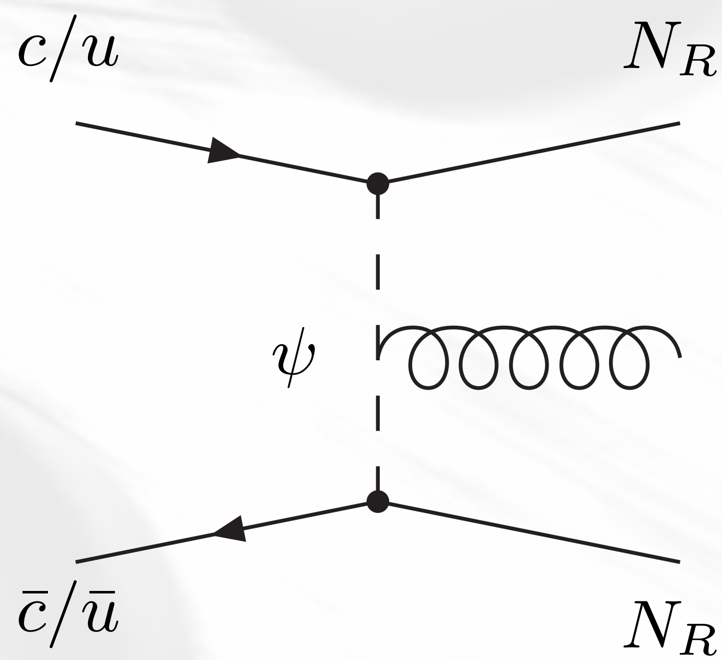

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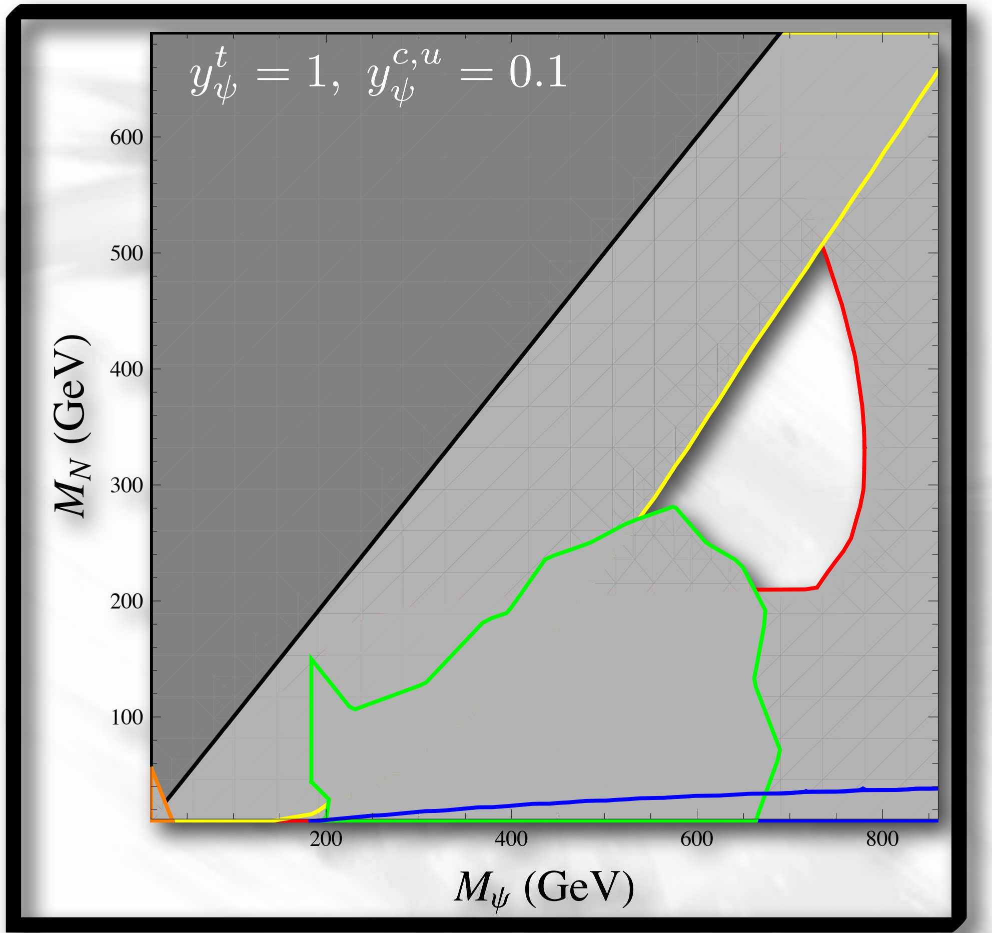
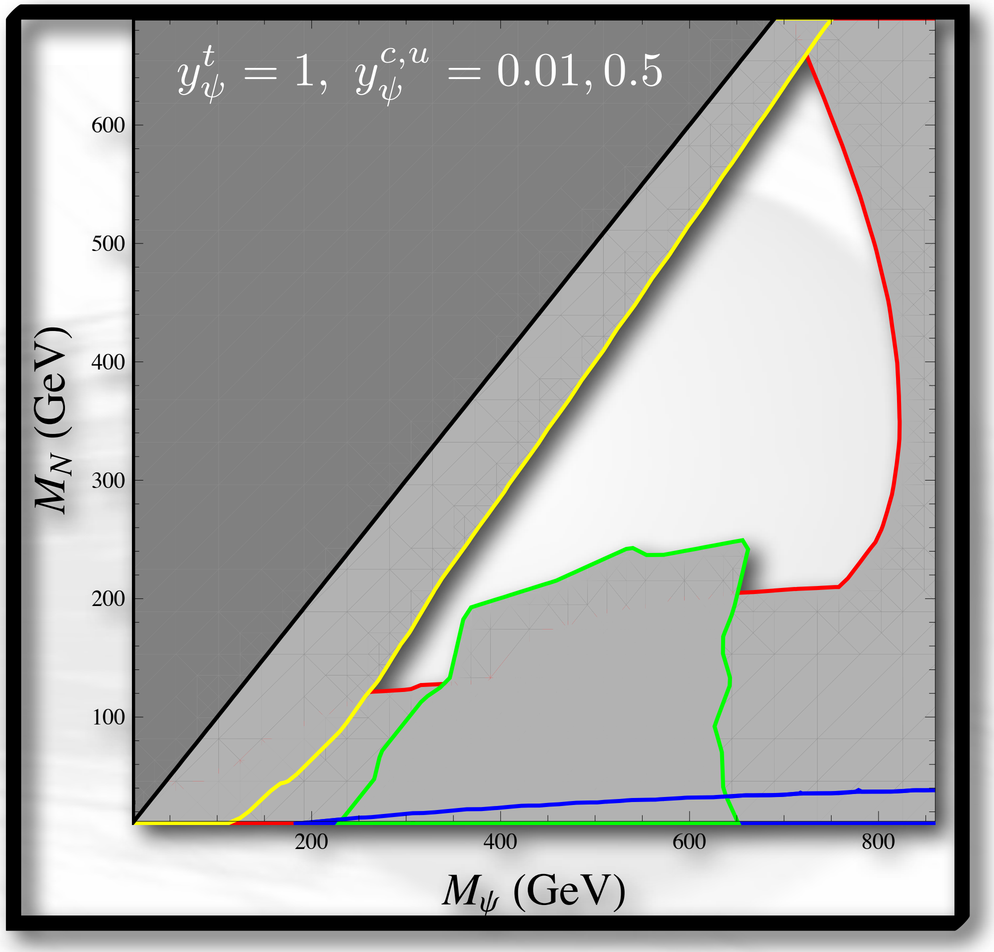
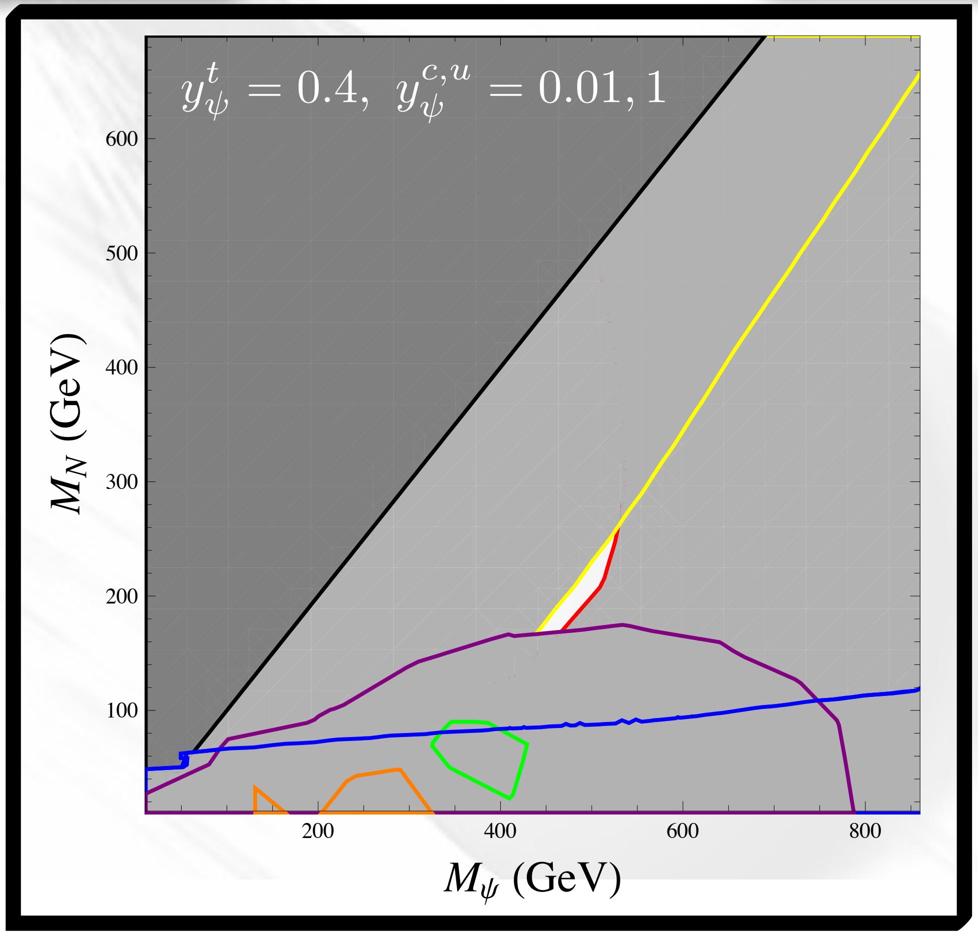
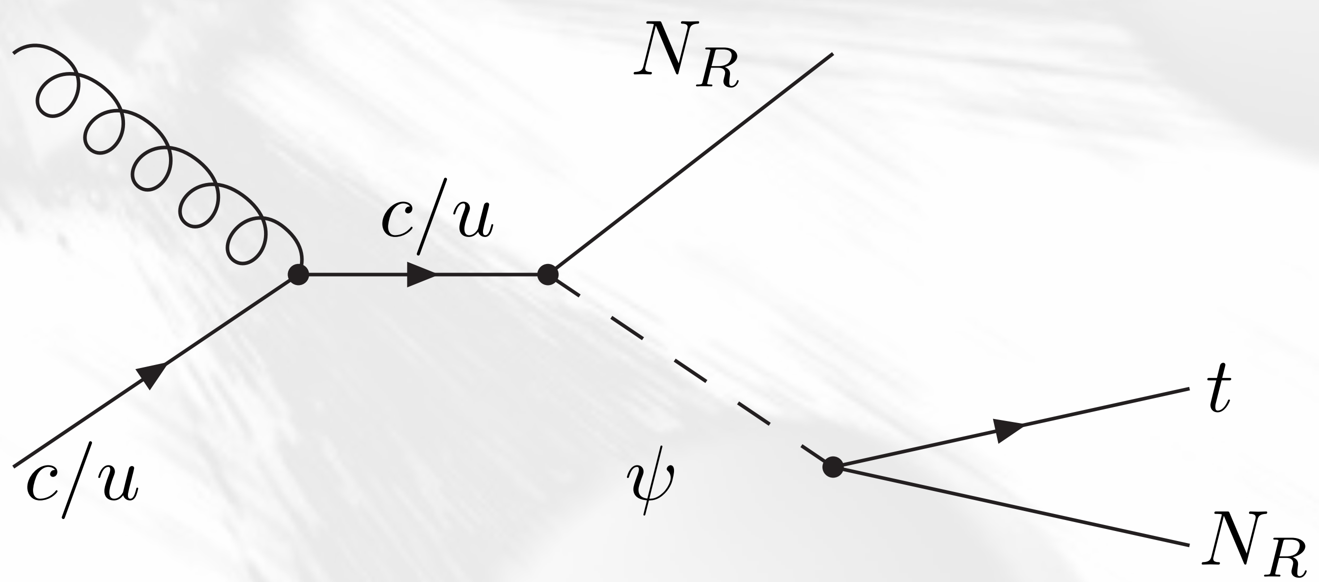

$y^t_\psi = 1,\ y^{c,u}_\psi = 0.1$
M_N (GeV)
M_ψ (GeV)
100
200
300
400
500
600
200
400
600
800


$y^t_\psi = 1,\ y^{c,u}_\psi = 0.01, 0.5$
M_N (GeV)
M_ψ (GeV)
100
200
300
400
500
600
200
400
600
800


$y^t_\psi = 0.4,\ y^{c,u}_\psi = 0.01, 1$
M_N (GeV)
M_ψ (GeV)
100
200
300
400
500
600
200
400
600
800

Monotop probe

- **Single top quark production in association with missing energy (MET) at the LHC.** arXiv:1106.6199



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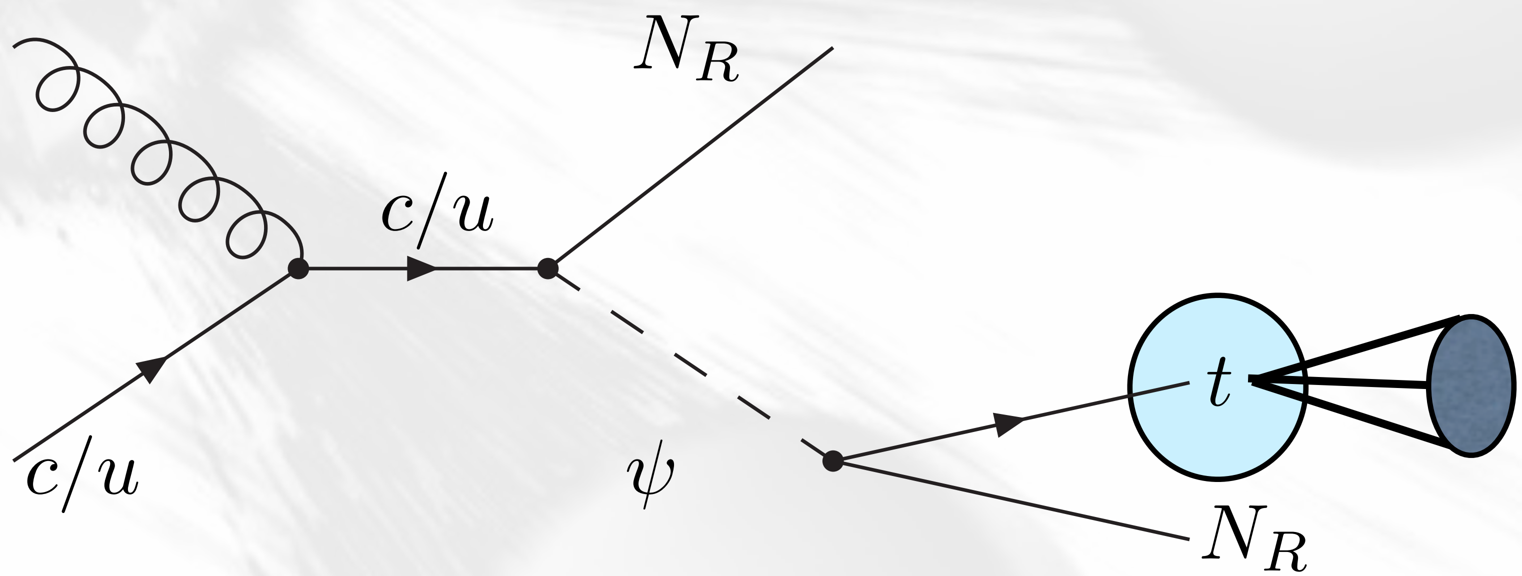


• **Apply search strategy for the hadronic and semi-leptonic decay modes of the top quark at 8 and 14 TeV.**

Hadronic mode signal 8 TeV:

$$t + N_R N_R \to bjj + N_R N_R$$

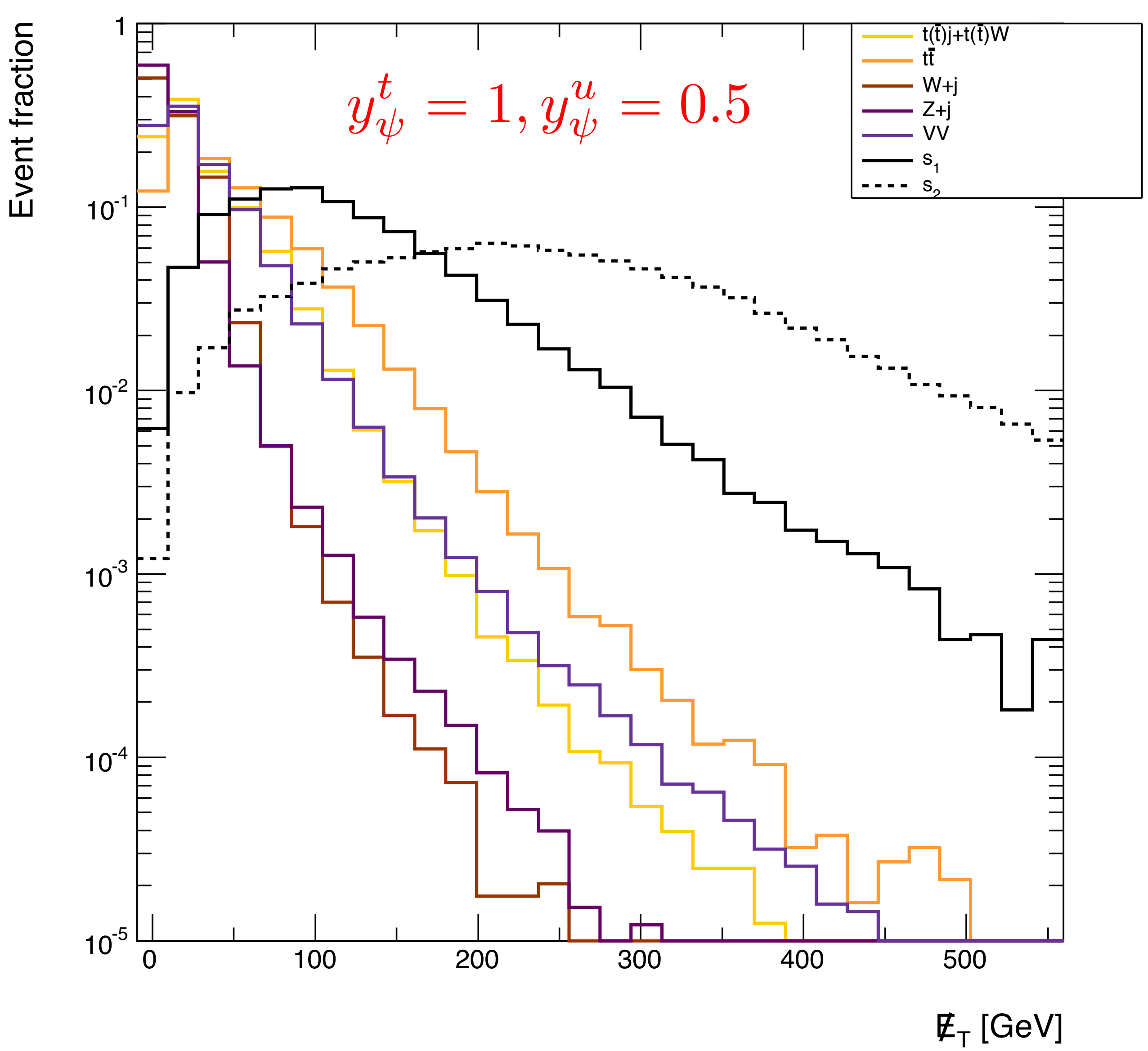
- **Main Backgrounds:**
  - $t\bar{t}$
  - $tj + tW$
  - Wj **and** Zj
  - **Di-boson**
  - **QCD multijet (Not simulated)**

Hadronic mode signal 8 TeV:

$$t + N_R N_R \to bjj + N_R N_R$$

- **Pre-selection:**
  - **Veto events with a lepton:** $p_T > 10 \text{ GeV}, \ |\eta| < 2.5$
  - **Require b-jets to have** $p_T > 50 \text{ GeV}, \ |\eta| < 2.5$.
  - **Light jets to have** $p_T > 30 \text{ GeV}, \ |\eta| < 2.5$.

Hadronic mode signal 8 TeV:



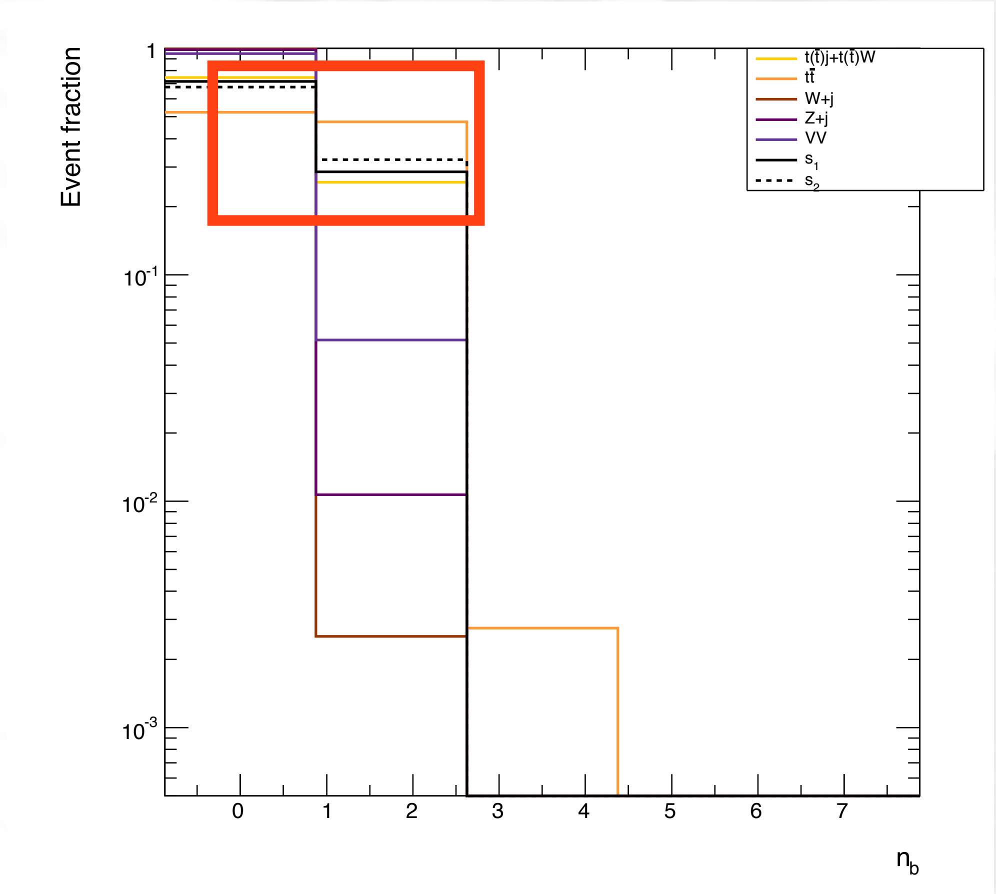
- Two signal regions defined by the amount of missing energy to probe the small and large m_ψ regions.

$$s_1 : m_\psi = 150 \text{ GeV}, M_{N_R} = 80 \text{ GeV}$$

$$s_2 : m_\psi = 700 \text{ GeV}, M_{N_R} = 210 \text{ GeV}$$

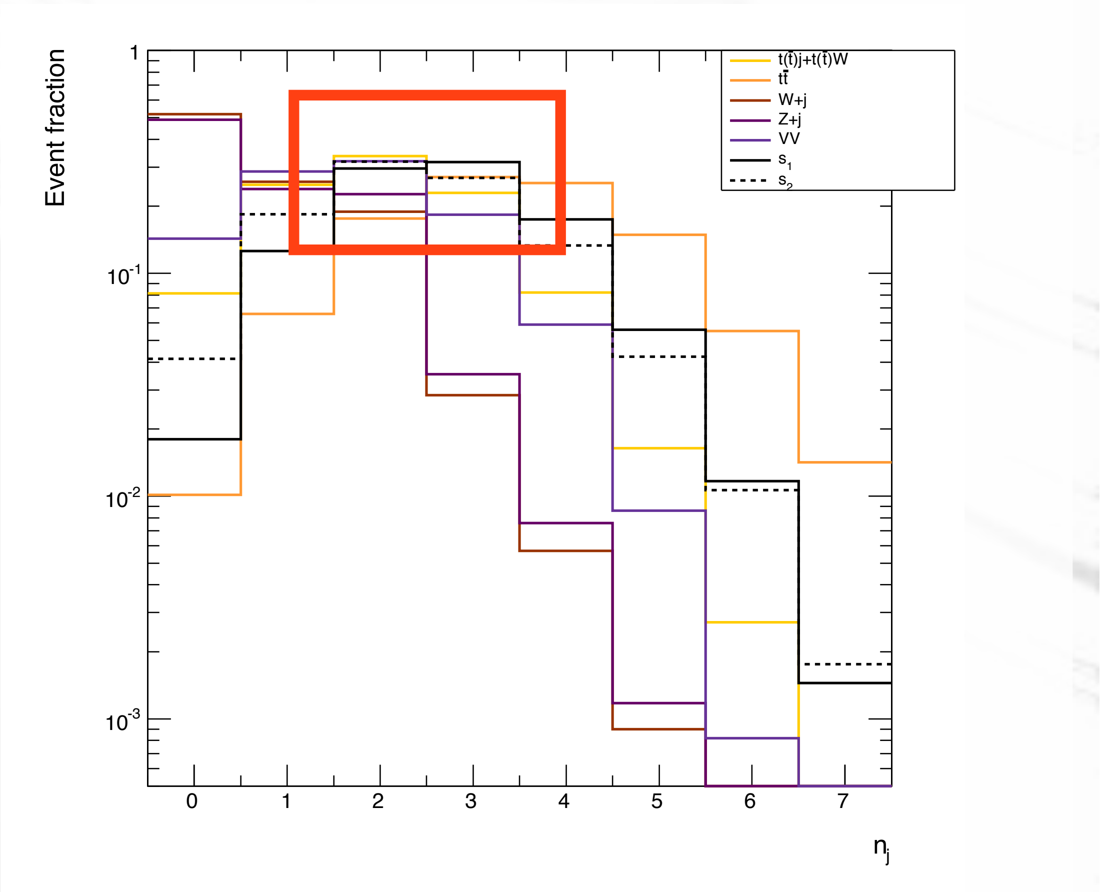
- **Pre-selection and large MET cut keep a good control of the QCD multijet background.**

Hadronic mode signal 8 TeV:



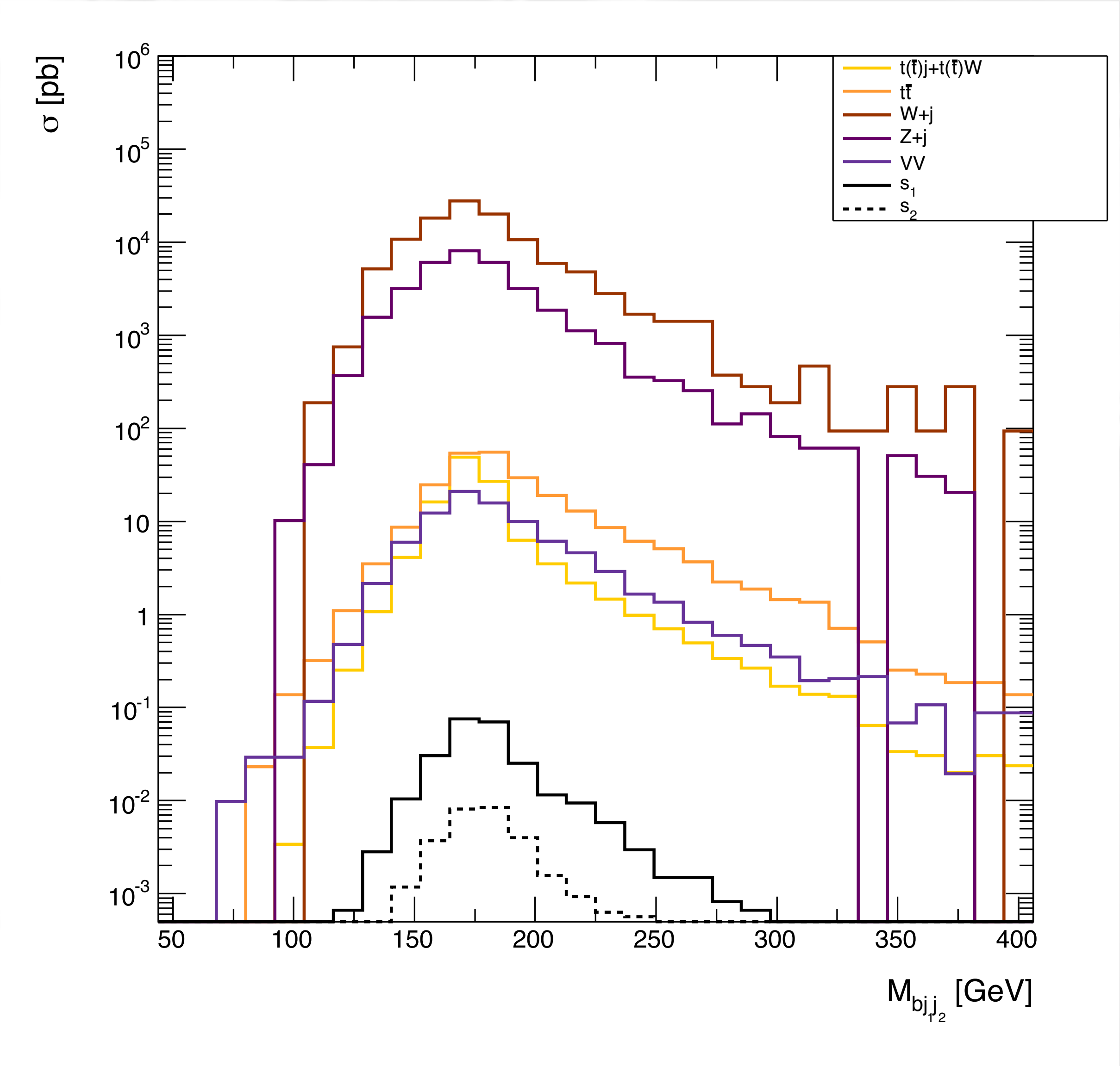
- Keep events with exactly 1 b-jet

- Keep events with 2 or 3 light jets



Hadronic mode signal 8 TeV:

- **Top mass reconstruction algorithm used by CMS.**



$$\chi^2 = \frac{(M_{bj_1j_2} - M_{top})^2}{\sigma^2_{bj_1j_2}} + \frac{(M_{j_1j_2} - M_W)^2}{\sigma^2_{j_1j_2}}$$

Hadronic mode signal 8 TeV (20 fb^{-1}):

SM background	$N^{\not{E}>90\text{ GeV}}$ (σ [pb])	$N^{\not{E}>200\text{ GeV}}$ (σ [pb])
$W(\to l\nu)+$ jets	1925 (0.096)	137 (6.83×10^{-3})
$Z+$ jets	420 (0.021)	<3 ($<1.54\times10^{-4}$)
$t\bar{t}+$ jets	11080 (0.55)	344 (0.017)
$t\,j+t\,W$	892 (0.044)	37 (1.84×10^{-3})
WW	17 (8.60×10^{-5})	<1 ($<5.73\times10^{-5}$)
WZ	22 (1.12×10^{-3})	2 (9.15×10^{-5})
ZZ	11 (5.72×10^{-4})	1 (4.76×10^{-5})

- 1 b-jet
- 2-3 light jets.
- $50 < M_{jj} < 105$ GeV, $140 < M_{bjj} < 195$ GeV.
- $\chi^2 < 5$

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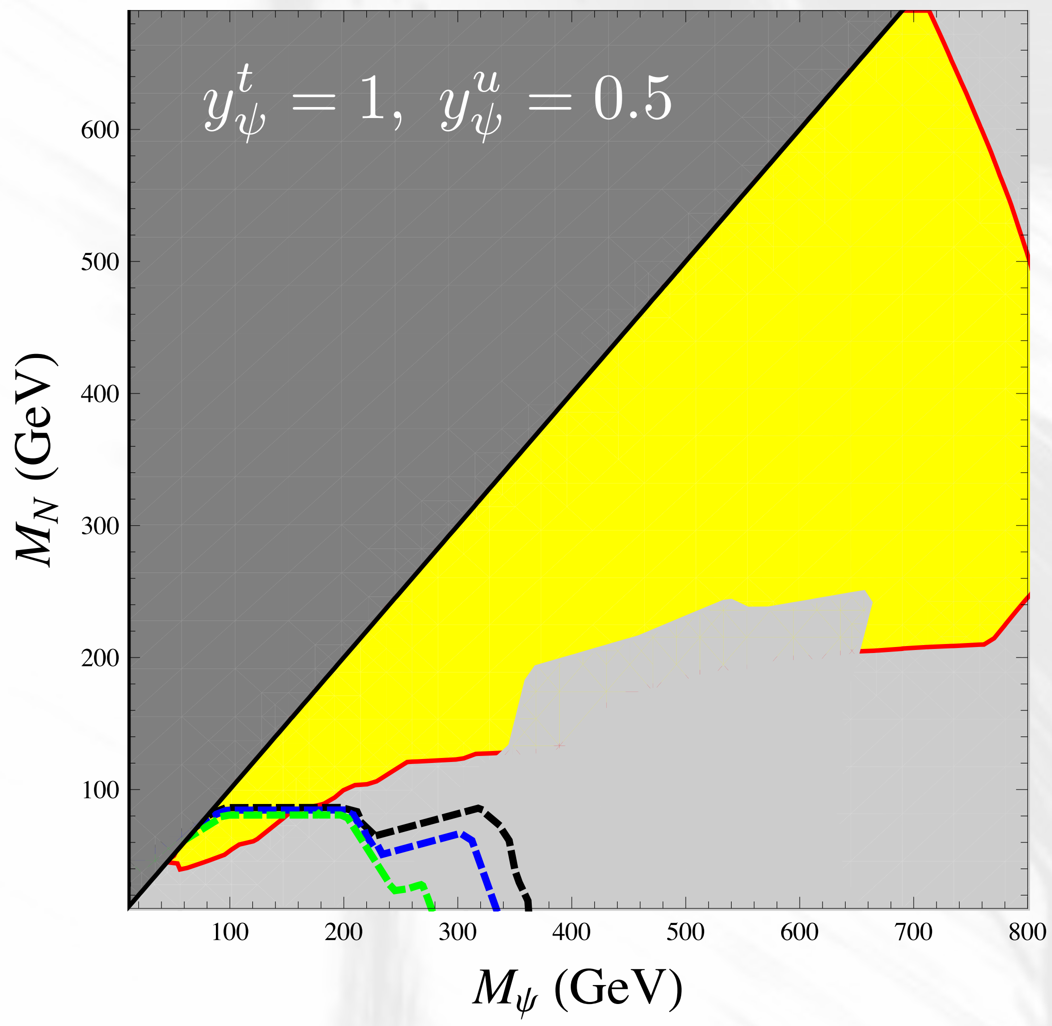
- Angular separation between leading light jet and MET as well as leading b-jet and MET: $\Delta\phi\left(p_{T(j,b)}, MET\right) > \pi/5$

ATLAS-CONF-2013-024

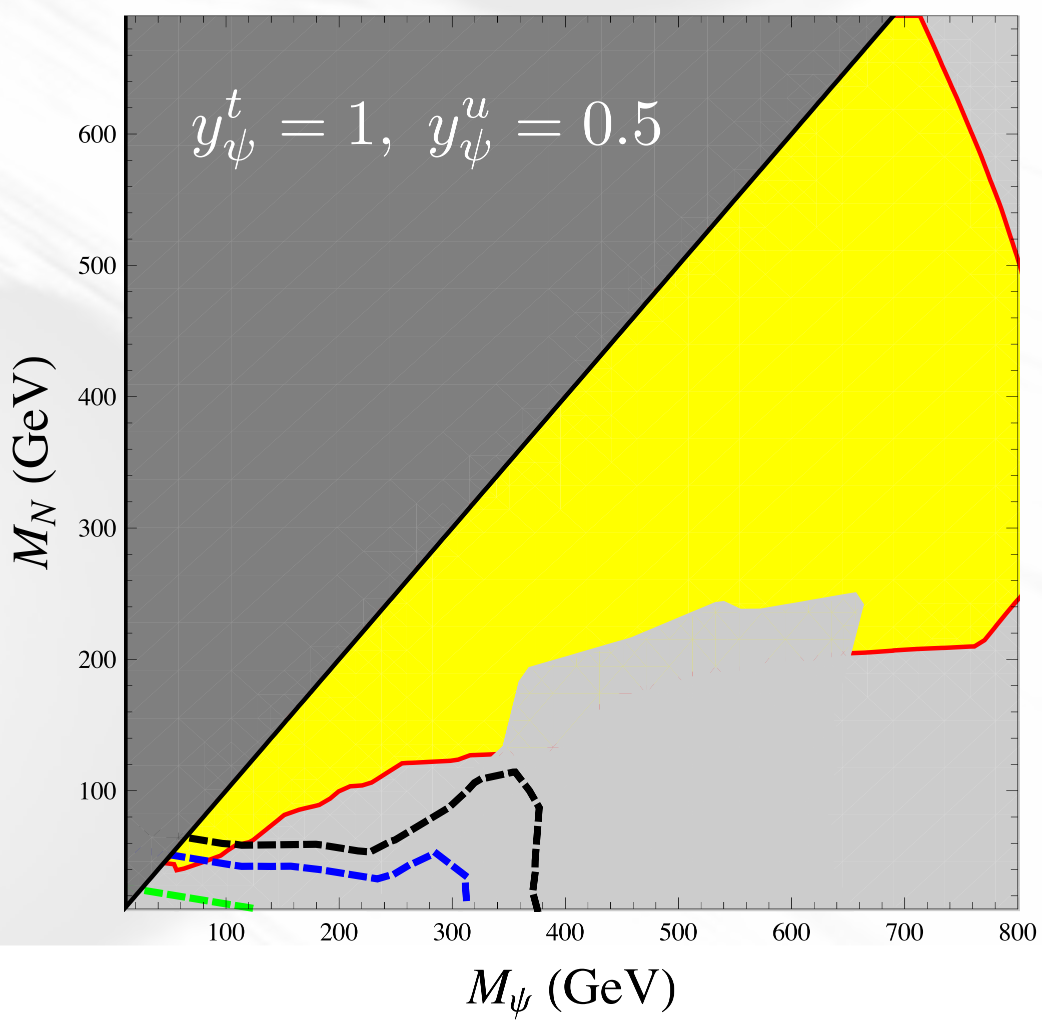
Hadronic mode signal 8 TeV (20 fb^{-1}):

$$S = \frac{s}{\sqrt{s+B}}$$



MET > 90 GeV

MET > 200 GeV



Semi-leptonic mode signal 8 TeV:

$$t + N_R N_R \to bl\nu + N_R N_R$$

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  - **Di-boson**

Semi-leptonic mode signal 8 TeV:

$$t + N_R N_R \to bl\nu + N_R N_R$$

- **Main Backgrounds:**
  - $t\bar{t}$
  - $tj + tW$
  - Wj **and** Zj
  - **Di-boson**
  - **Less likely to be contaminated by QCD multijet background. Little contamination from mis-reconstructed jet (p_T cut) .**

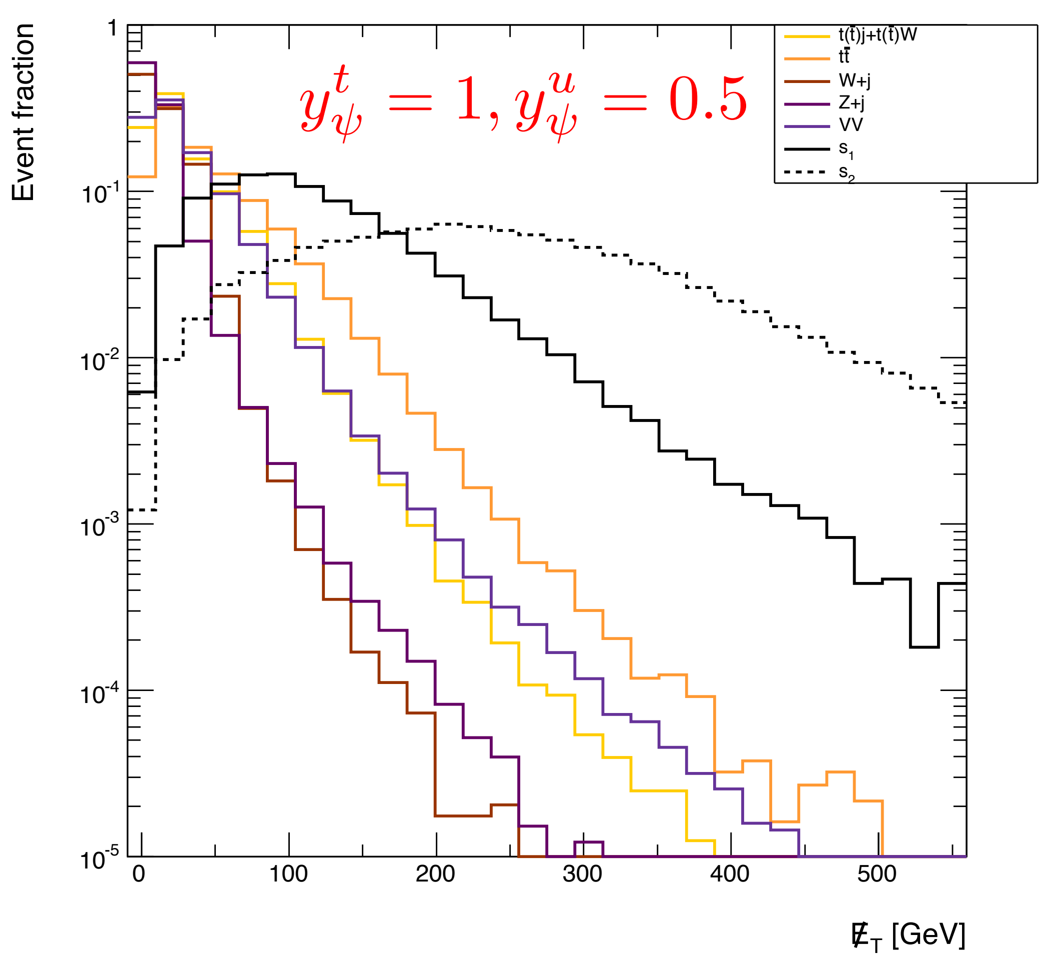
Semi-leptonic mode signal 8 TeV:

$$t + N_R N_R \to bl\nu + N_R N_R$$

- **Pre-selection:**
  - **Require events with a lepton:** $p_T > 20$ GeV, $|\eta| < 2.5$
  - **Require one b-jet to with** $p_T > 20$ GeV, $|\eta| < 2.5$.
  - **At most one light jet.** .

arXiv:1310.7600

Semi-leptonic mode signal 8 TeV:



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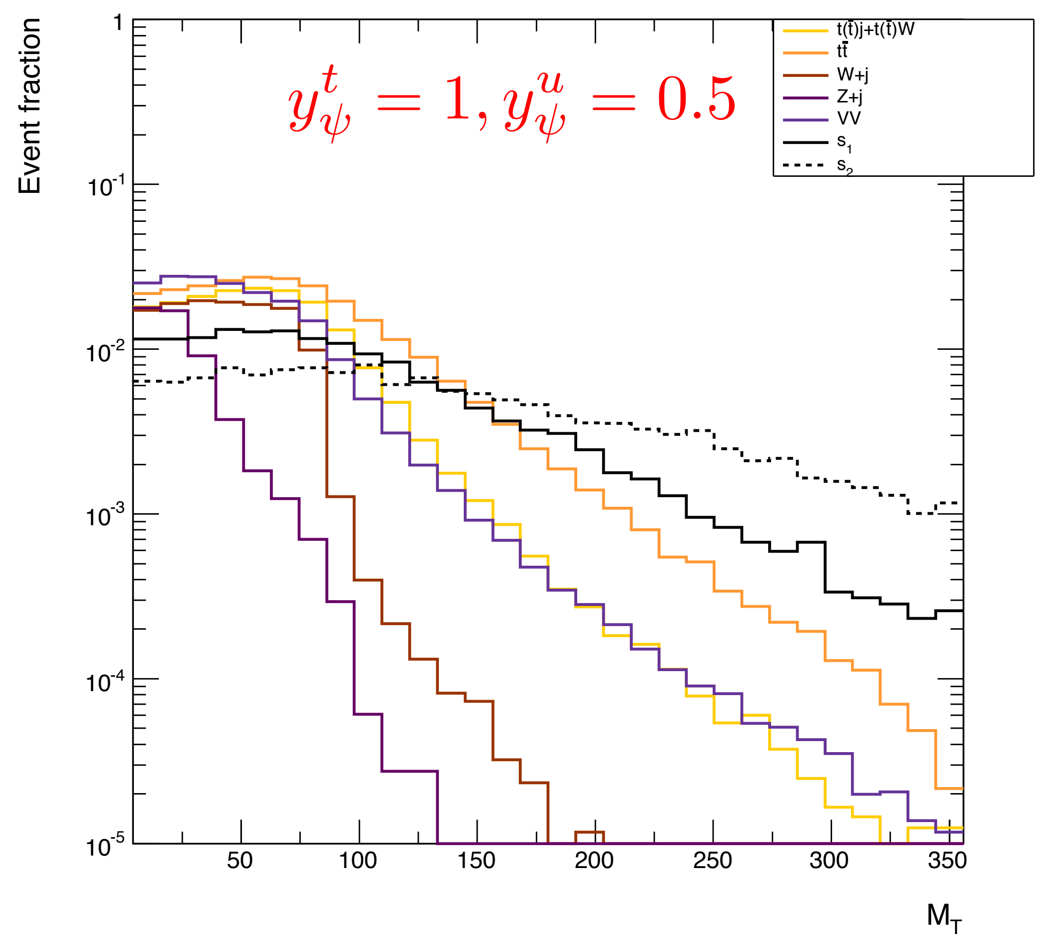

Semi-leptonic mode signal 8 TeV (20 fb^{-1}):

SM background	$N^{\not{E}>90\text{ GeV},M_T>110\text{ GeV}}$ (σ [pb])	$N^{\not{E}>200\text{ GeV},M_T>120\text{ GeV}}$ (σ [pb])
$W(\to l\nu)+$ jets	212 (0.011)	< 7 ($< 3.41 \times 10^{-4}$)
$Z+$ jets	< 3 ($< 1.54 \times 10^{-4}$)	< 3 ($< 1.54 \times 10^{-4}$)
$t\bar{t}+$ jets	1327 (0.066)	49 (2.46×10^{-3})
$t\ j + t\ W$	242 (0.012)	< 2 ($< 1.15 \times 10^{-4}$)
WW	2 (1.15×10^{-4})	< 1 (5.73×10^{-5})
WZ	1 (6.86×10^{-5})	*** ($< 2.29 \times 10^{-5}$)
ZZ	*** ($< 7.94 \times 10^{-6}$)	*** ($< 7.94 \times 10^{-6}$)

- 1 b-jet
- 0-1 light jets with $p_{T,j} < 70$, 120 GeV.

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- **Missing energy from mis-reconstructed jets.**

- **1 b-jet**
- **0-1 light jets with $p_{T,j} < 70, 120$ GeV.**

arXiv:1310.7600

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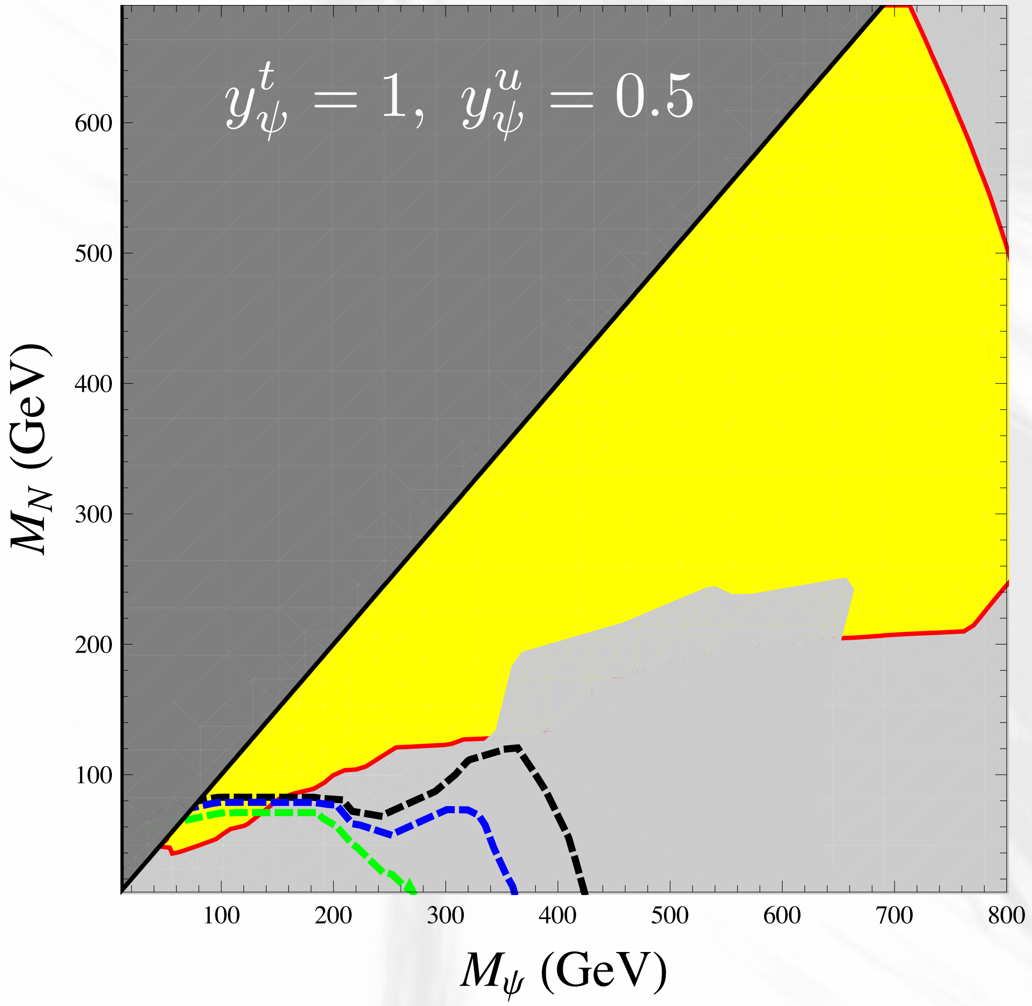
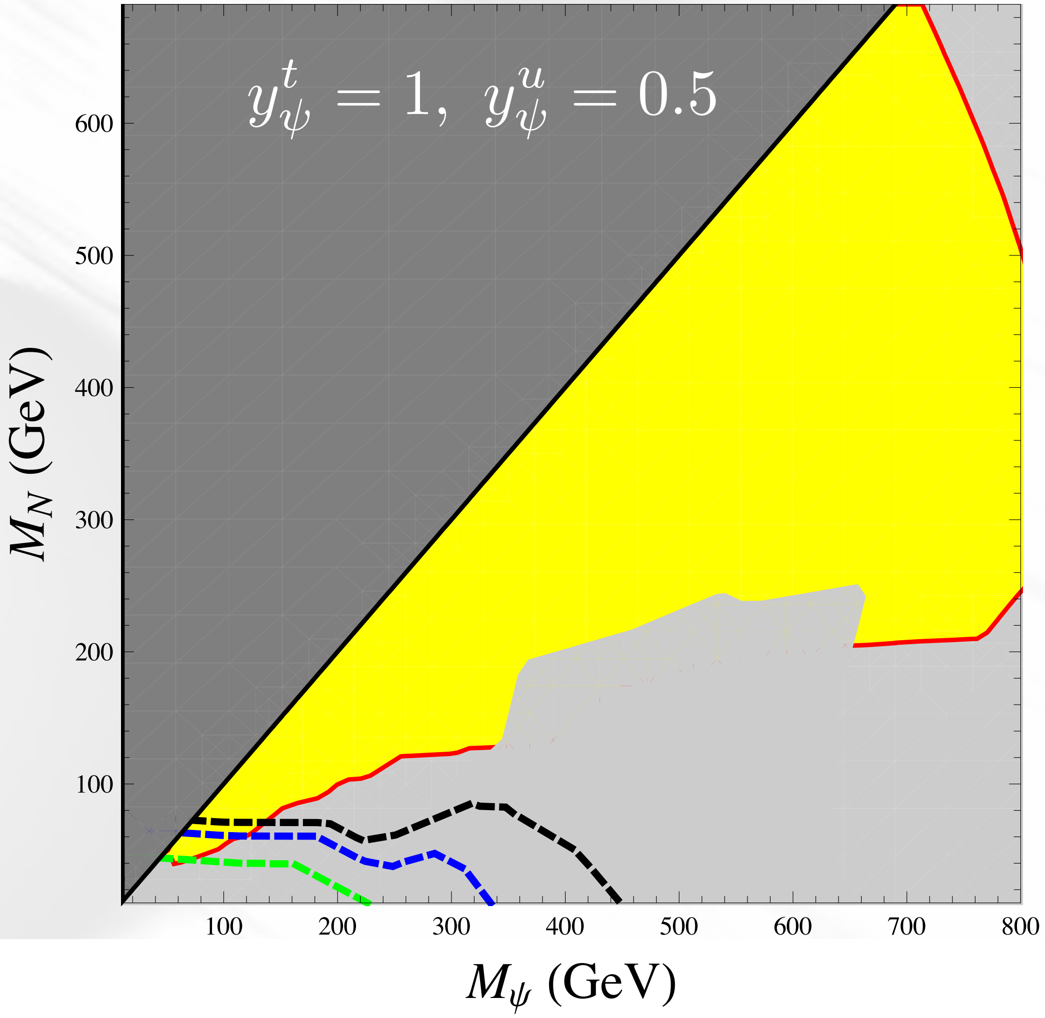


MET > 200 GeV, M_T > 120 GeV

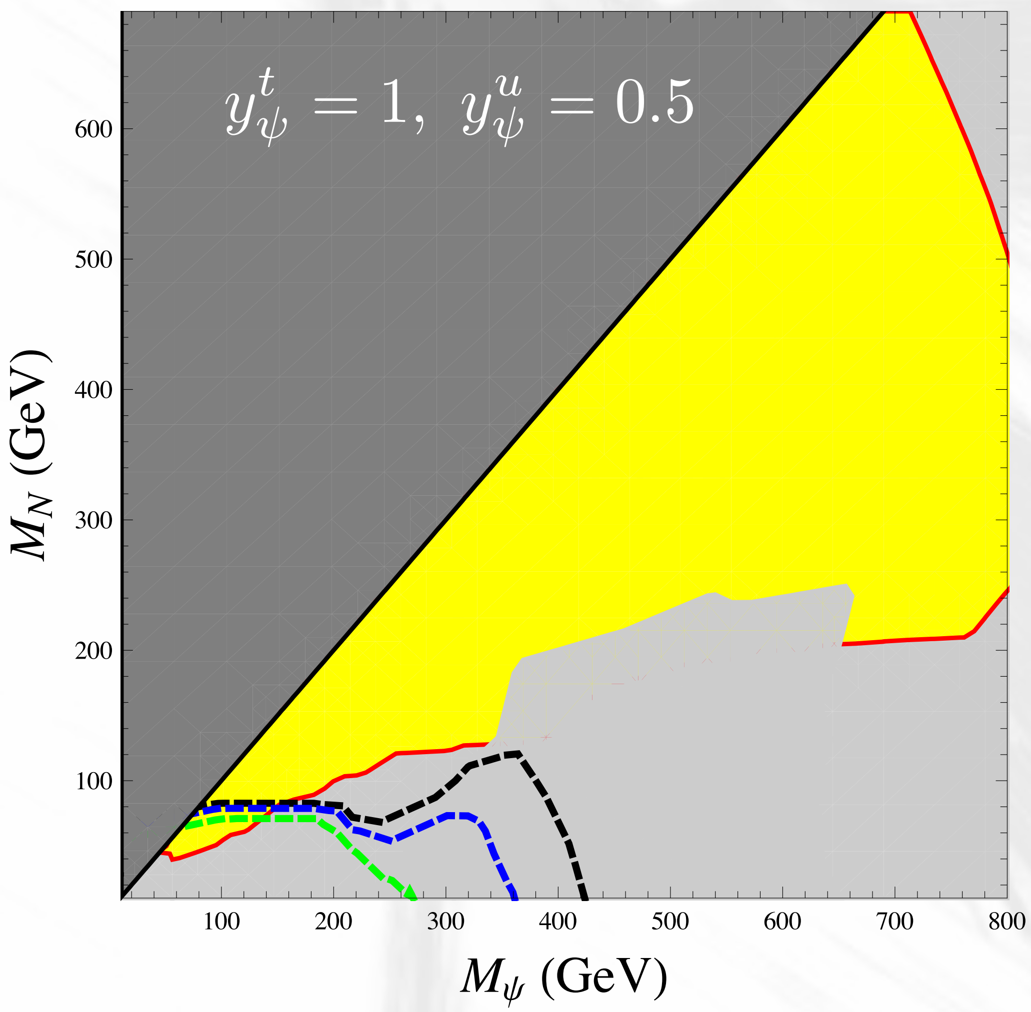


MET > 90 GeV, M_T > 110 GeV

Semi-leptonic mode signal 8

- **Signal significance similar to hadronic mode... but better control of QCD multijet background.**

MET > 200 GeV, M_T > 120 GeV



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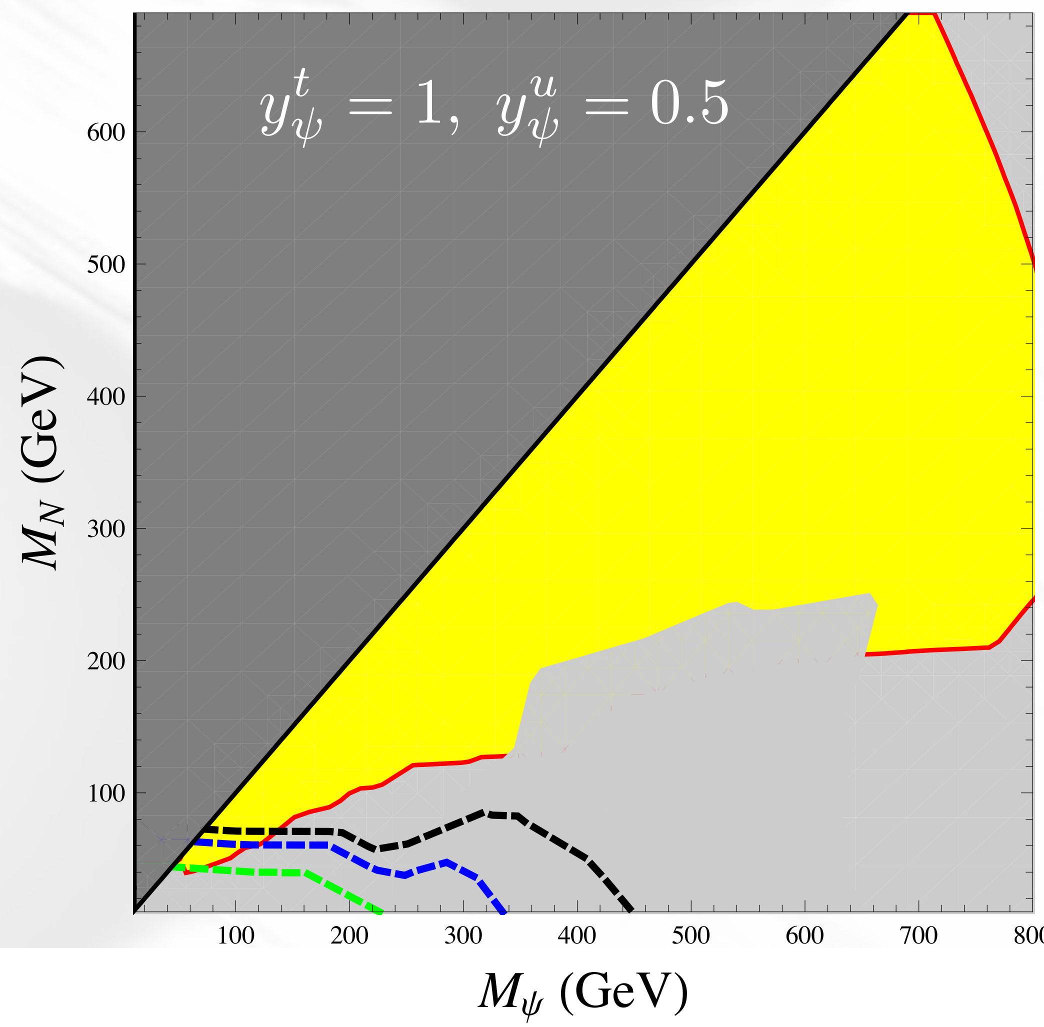

Semi-leptonic mode signal 14 TeV:

- **SM backgrounds using *k-factors* from 8 TeV cross sections.**
- **Wj and Zj backgrounds suppressed by a combination of lepton isolation, b-tagging and M_T cuts.**
- **However, for large collider energies, a large MET cut is necessary.**

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Process	σ [pb]
$W+$ jets	2.19×10^5
$Z+$ jets	6.66×10^4
$t\bar{t}+$ jets	1052.93
$tj+tW$	347.42
WW	119.84
WZ	48.87
ZZ	17.09

$y_\psi^t = 1,\ y_\psi^u = 0.5,\ m_\psi = 700$ GeV$,\ M_{N_R} = 210$ GeV

$\mathcal{L}$ [fb^{-1}]	σ ($t\bar{t}+$jets) [pb], N	σ ($tj+tW$) [pb], N	σ_{signal}[pb], N
30	6.31×10^{-3}, 189	1.39×10^{-3}, 42	6.85×10^{-4}, 21
300	1892	417	205

- **MET > 200 GeV, M_T > 120 GeV and $p_{T,j}$ < 120 GeV**

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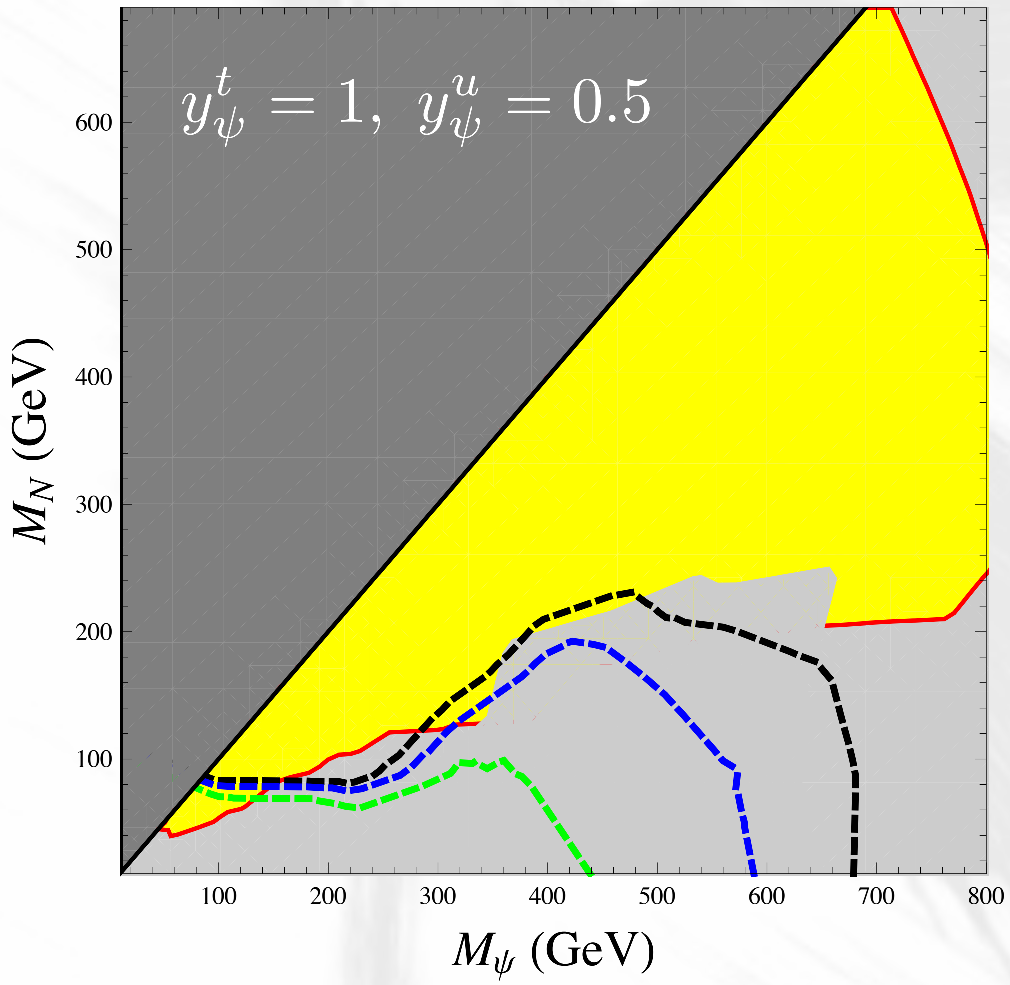
$\mathcal{L}$ [fb^{-1}]	σ ($t\bar{t}$ + jets) [pb], N	σ ($tj + tW$) [pb], N	
30	6.31×10^{-3}, 189	1.39×10^{-3}, 42	$S = 1.3$
300	1892	417	$S = 4.1$

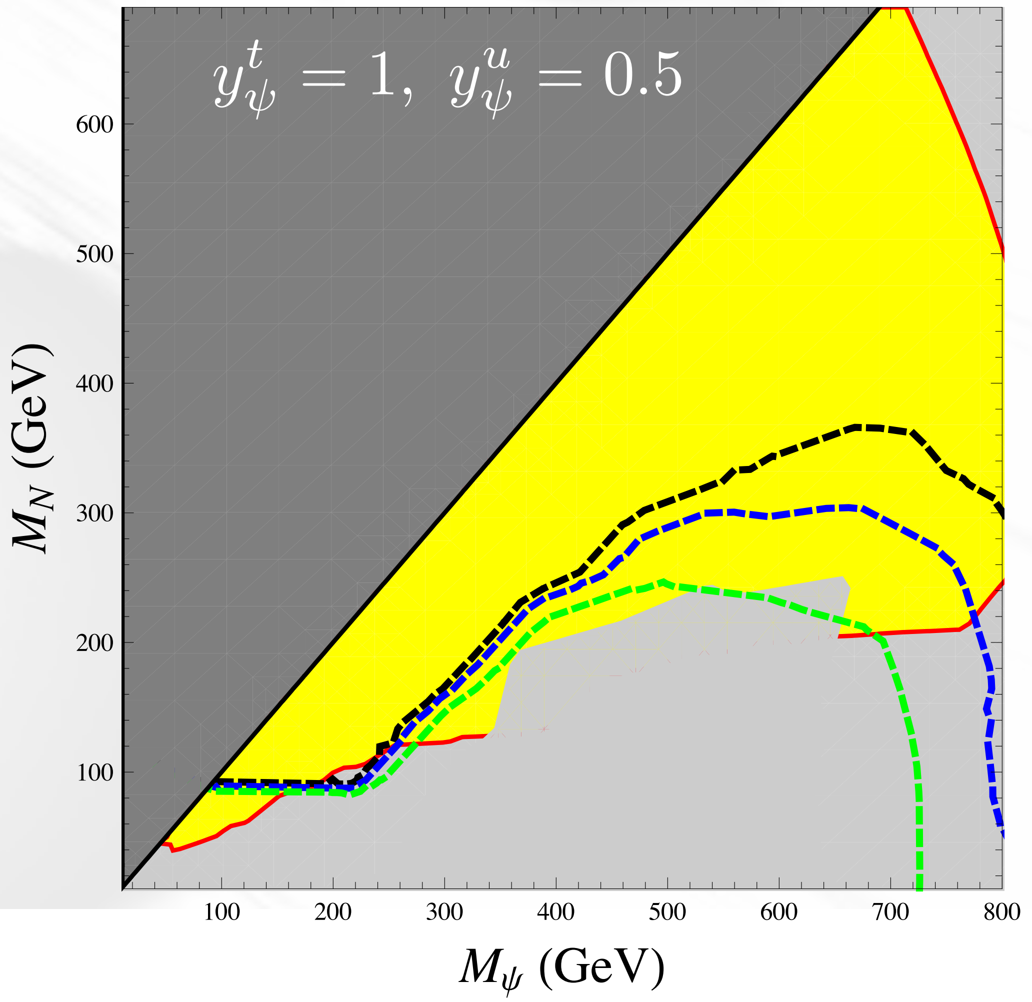
- MET > 200 GeV, M_T > 120 GeV and $p_{T,j}$ < 120 GeV

Semi-leptonic mode signal 14 TeV:



L = 30 fb^{-1}

L = 300 fb^{-1}



Summary

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• Next run at the LHC may begin to probe monotop production.

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- We must use not only astrophysical resources to address the nature of dark matter but the power of hadron colliders.
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- Next run at the LHC may begin to probe monotop production.
- It may lead to evidence of the underlying mechanism the bestows neutrinos with mass.